Basic Principles and Evidences of Wind Turbine Noise Generation Mechanisms

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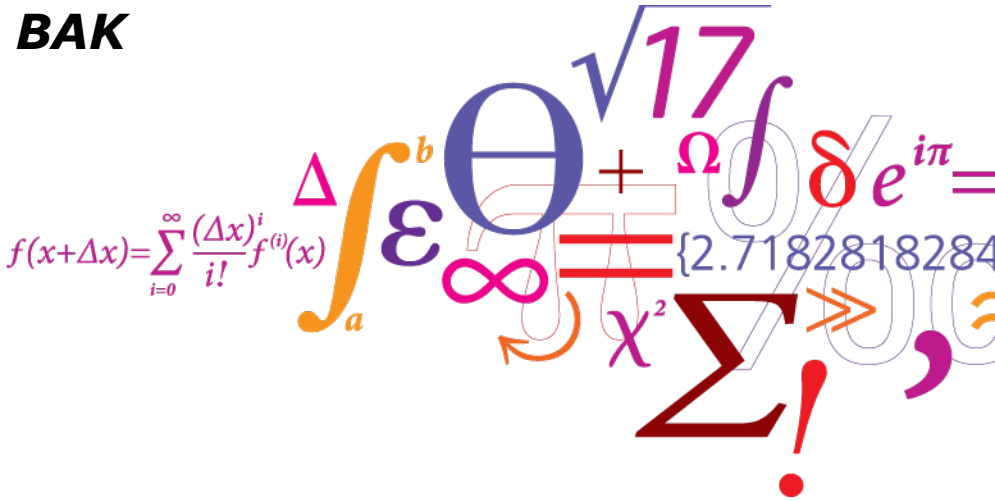


DTU Wind Energy
Department of Wind Energy

Outline

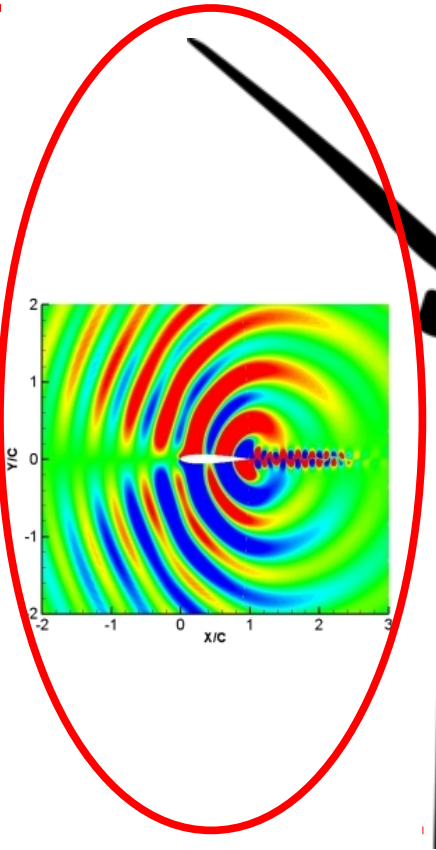
Two main parts:

- **Physics of Sound Generation**
  - *Basic mechanisms of sound generation*
  - *Using analogies - No equations :-)*
  - *Mechanisms responsible of wind turbine noise*
- **Characterization of wind turbine noise sources**
  - *Using surface pressure microphones*
  - *Measurements performed on a 2MW wind turbine*
- **Conclusions**

WIND TURBINE NOISE

Noise generation mechanisms

Aerodynamic and/or Mechanical noise

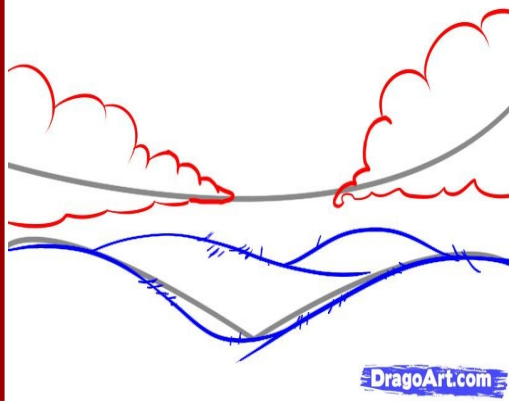


Wind turbine noise

As it can be measured in the direct vicinity of the wind turbine & As used for WT noise assessment

Propagation of sound

Atmospheric conditions, Orography, Vegetation, Refraction, Diffraction



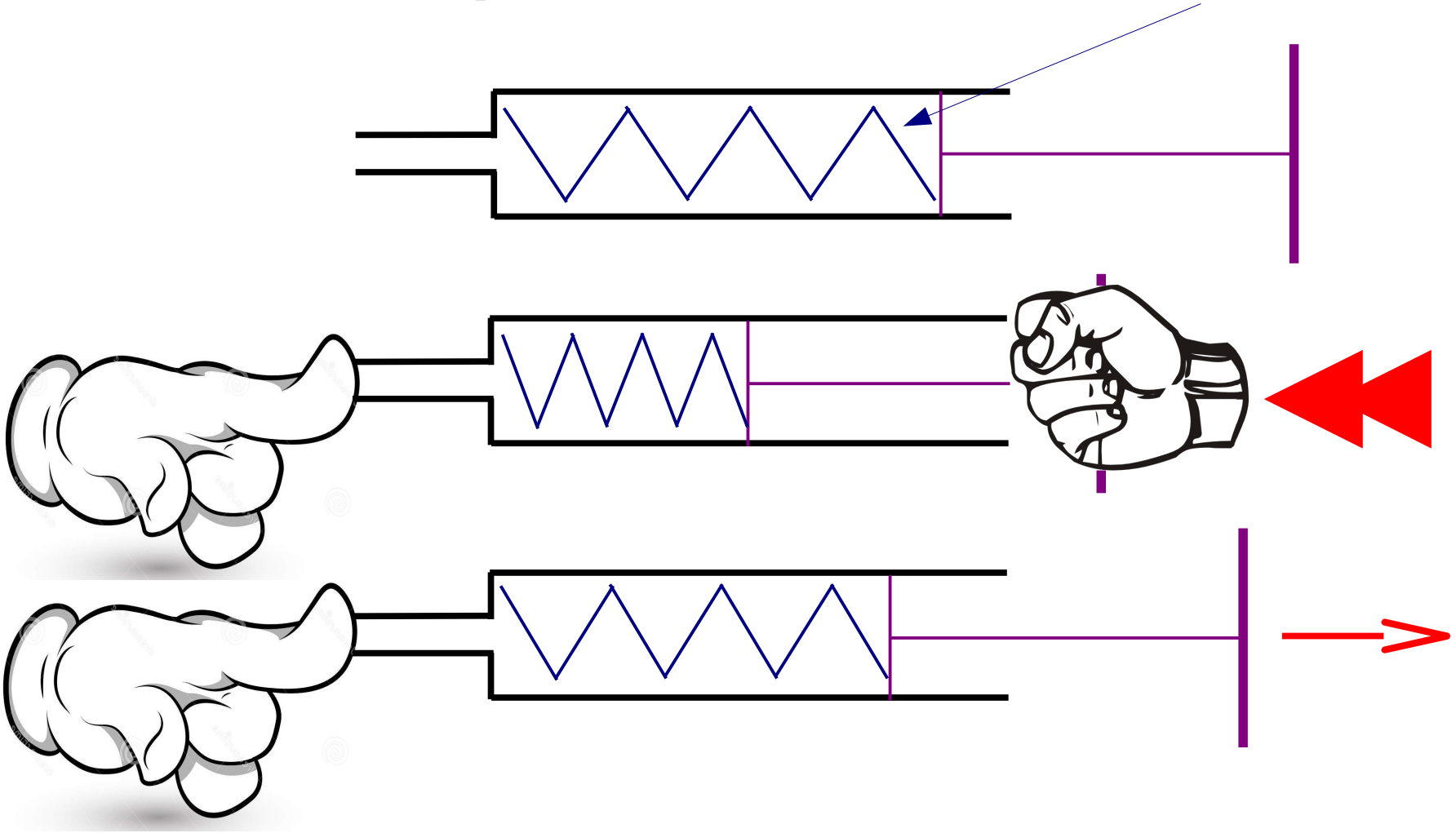
Perception of sound by receiver

More subjective, Sensitivity of individual, Quality of noise, Home insulation

The Physics of Sound Generation

Analogy:

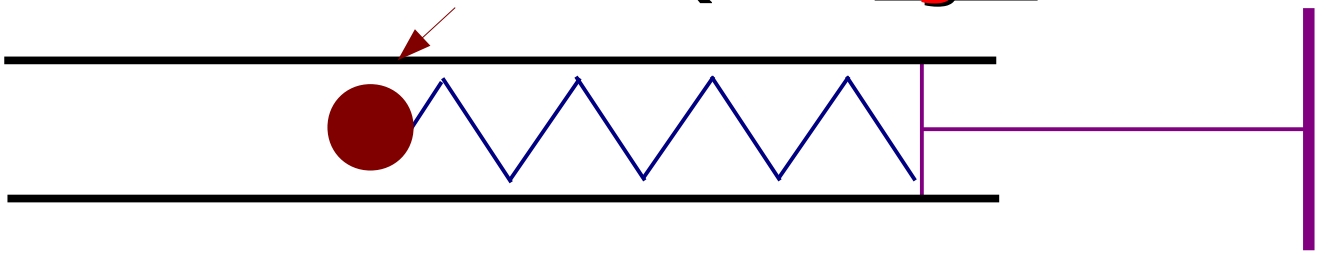
- The **AIR** is ***compressible*** = acts as a ***SPRING***!



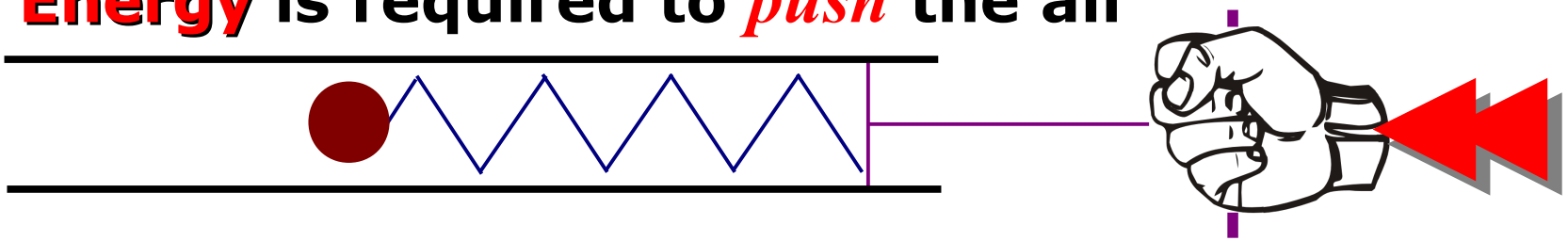
The Physics of Sound Generation

Analogy:

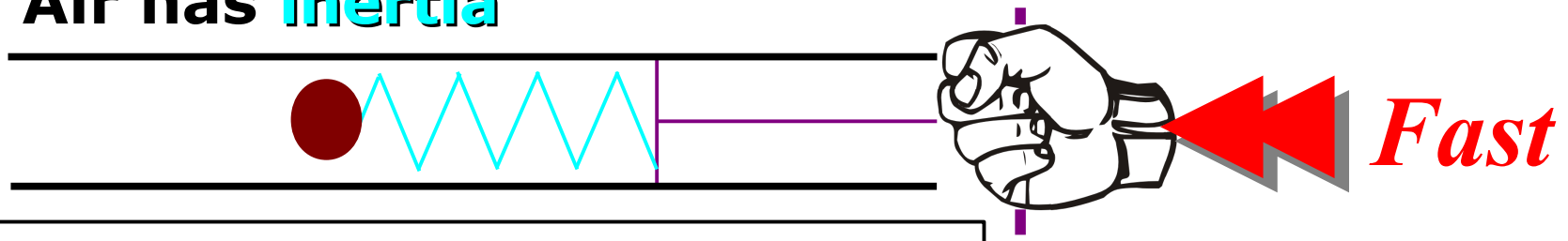
- The AIR has a ***MASS***! (it is **light but still…!!!**)



- Two **important consequences**:
  - **Energy** is required to *push* the air



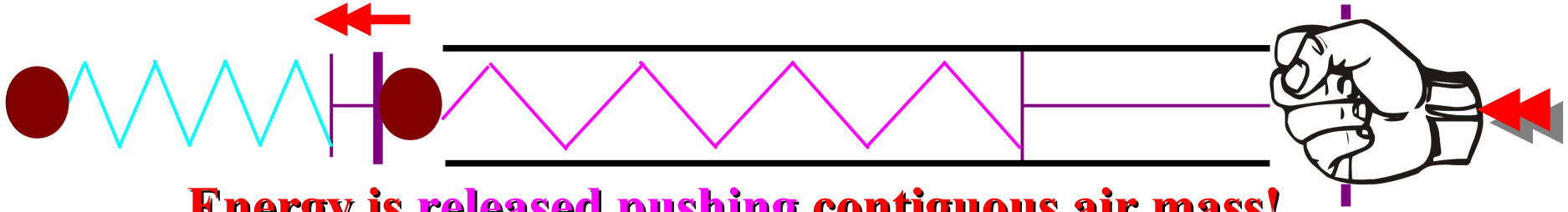
  - Air has **inertia**



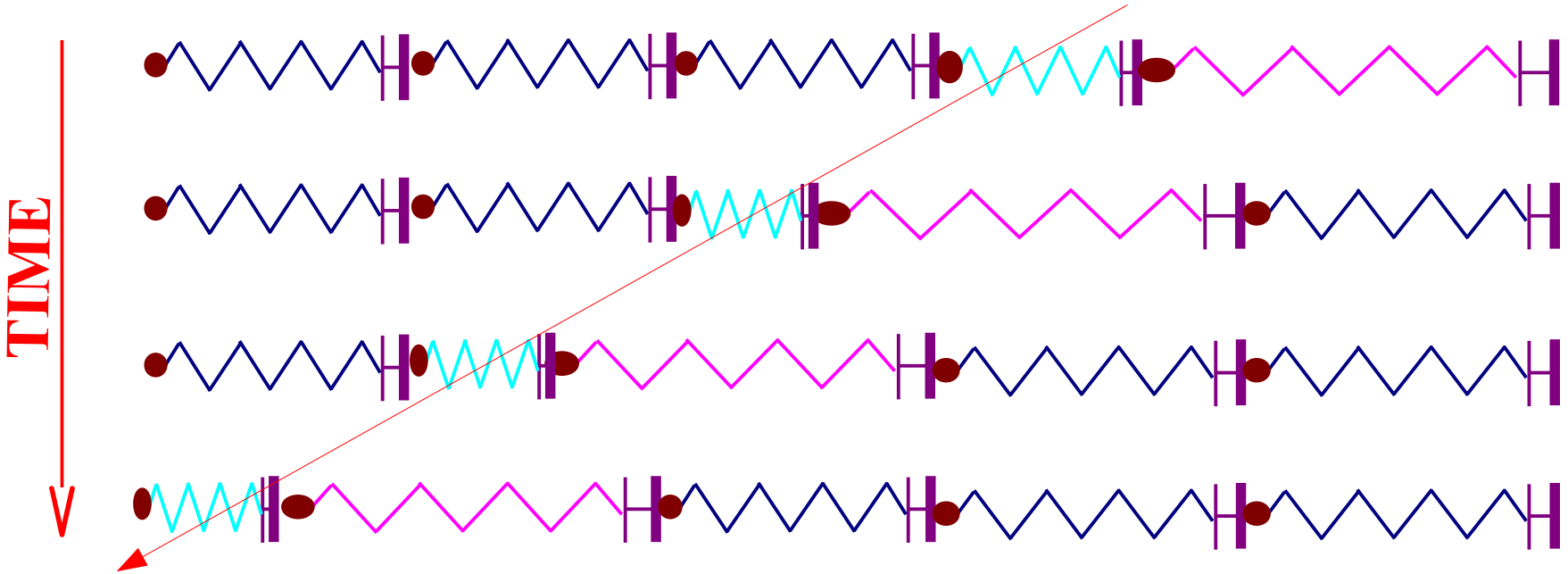
Energy is stored = Compressed air!

The Physics of Sound Generation

Analogy: ➢ The *AIR* = *MASS* + *SPRING*



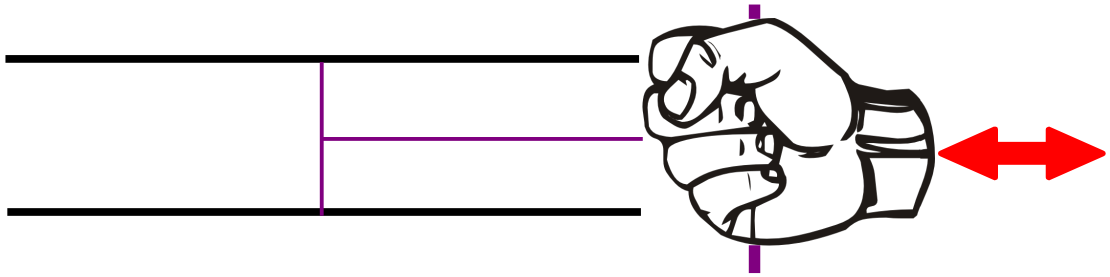
Energy is released pushing contiguous air mass!



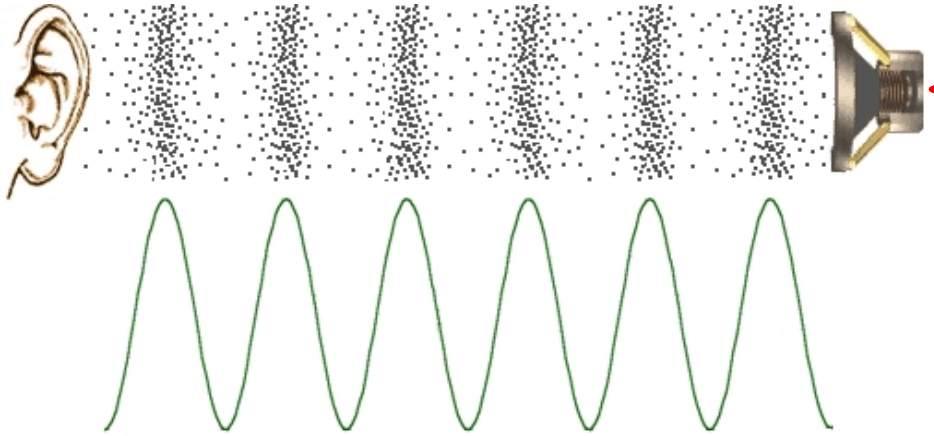
Travelling wave **at $C_0 \approx$ 340 m/s = SPEED OF SOUND**

The Physics of Sound Generation

=*Working principle of a loudspeaker:*



SPEED = $C_0 \approx 340$ m/s



Very fast:

1000 times/second

= 1000 Hertz

= *Frequency*

Very efficient loudspeaker only converts 5% of the energy into sound energy (dB)

The Physics of Sound Generation

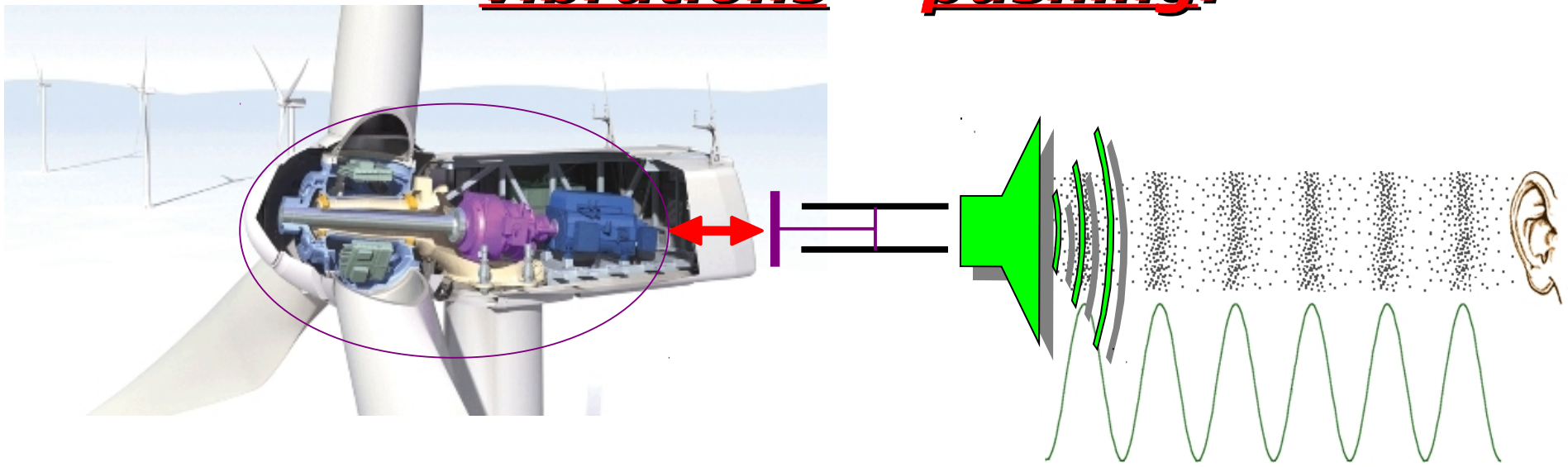
Wind turbine mechanical noise

Nacelle components act as loudspeakers!

Shaft+Gear+Generator rotate

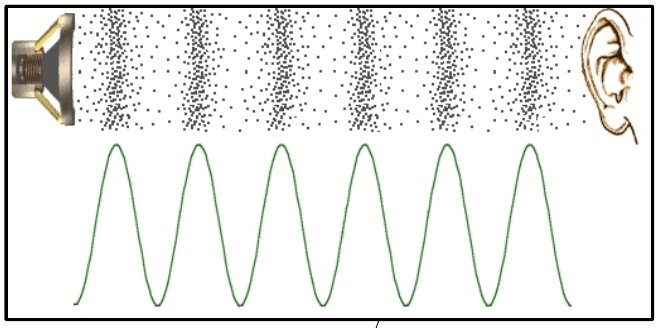
and may be *slightly unbalanced* or *misaligned*

generating (eigen-)modal *structural vibrations* = *pushing!*

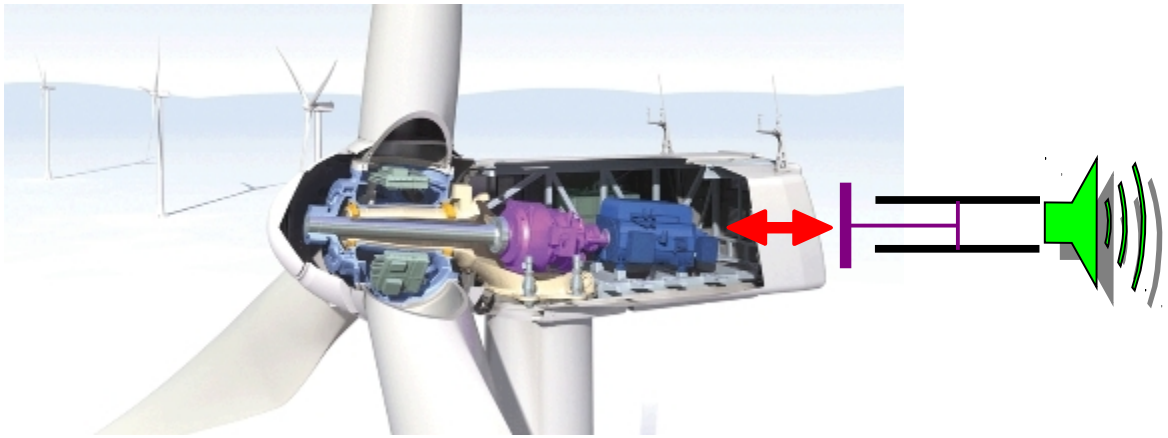


The Physics of Sound Generation

Wind turbine mechanical noise is tonal:



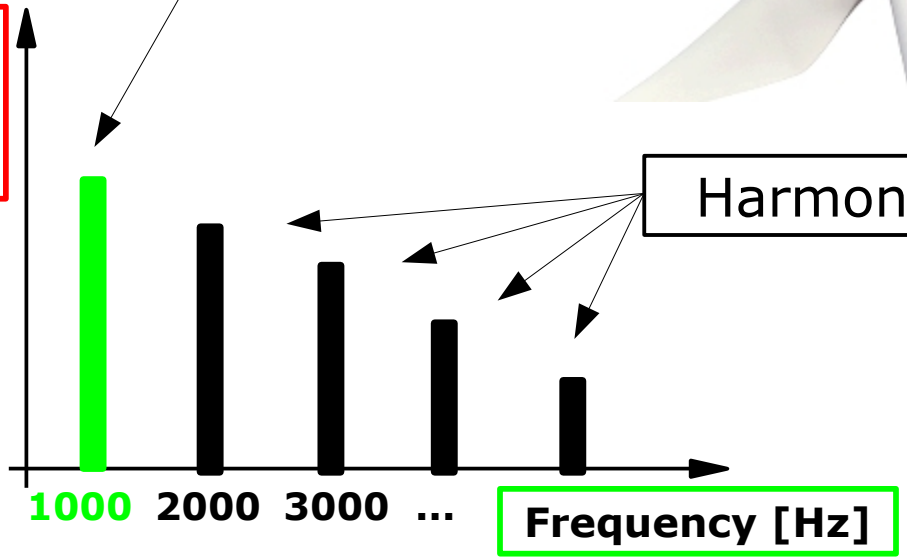
Narrow band noise



Noise Level [dB(A)]

=

Energy Level

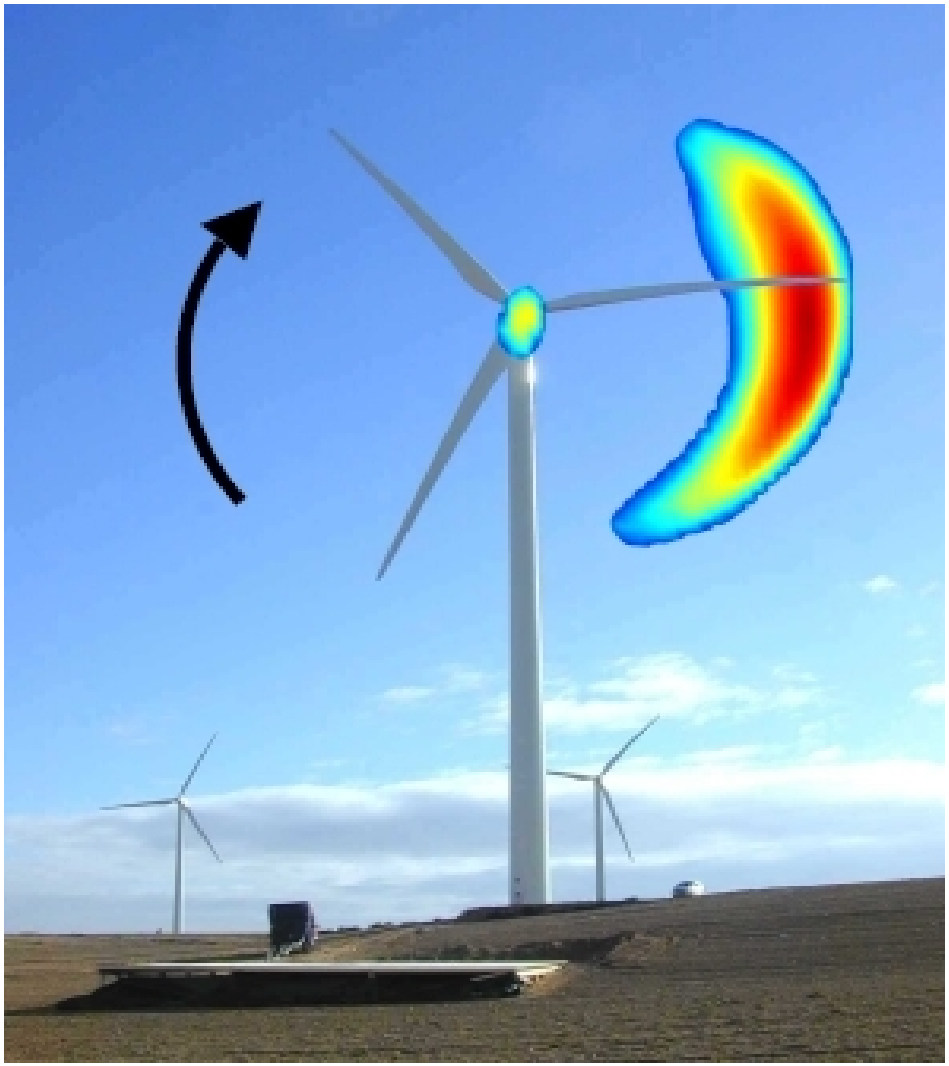


Energy Spectrum

The Physics of Sound Generation

Wind turbine noise visualization:

Oerlemans and Schepers, NLR [2009]



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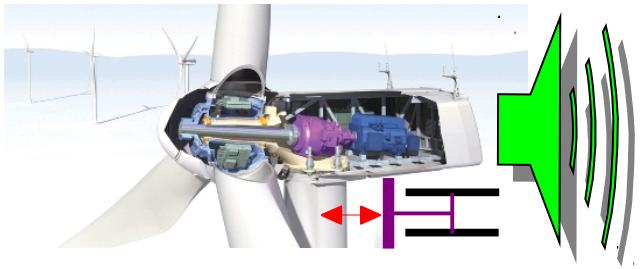
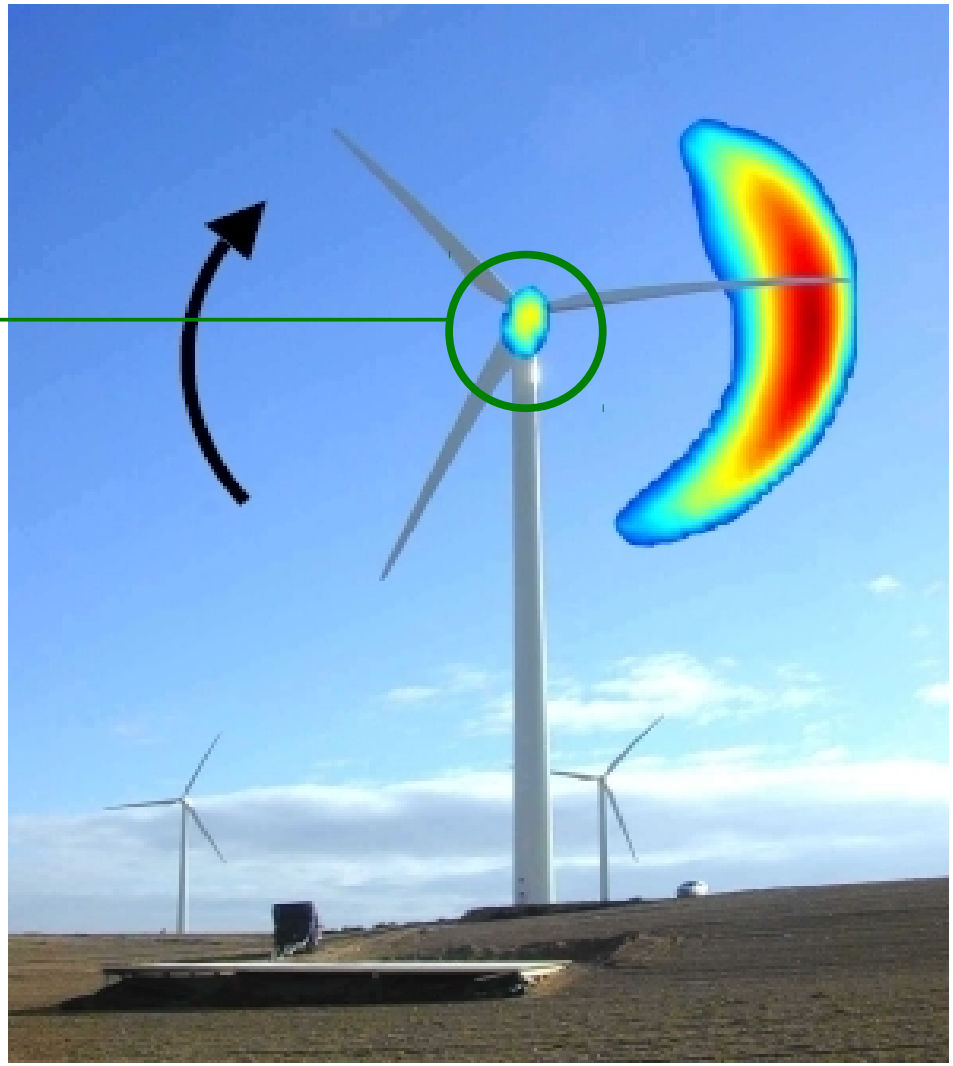
Wind turbine noise visualization:



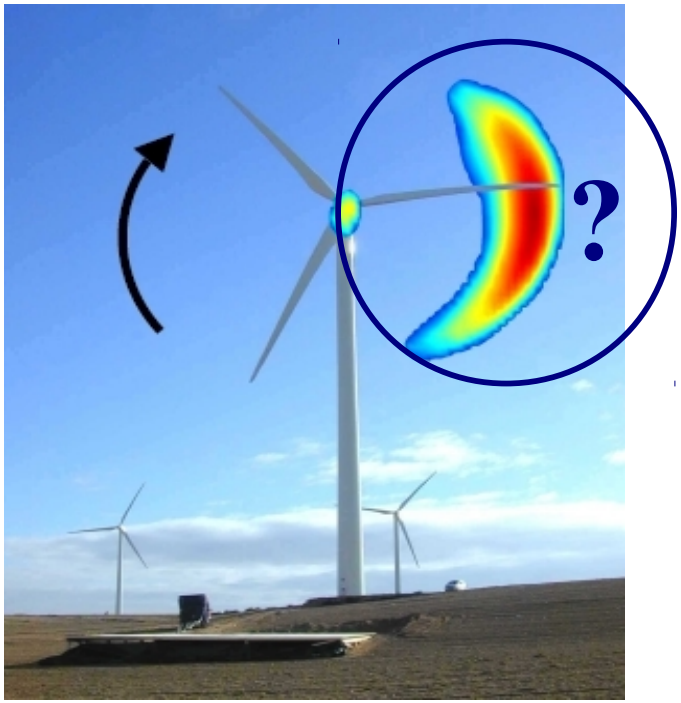


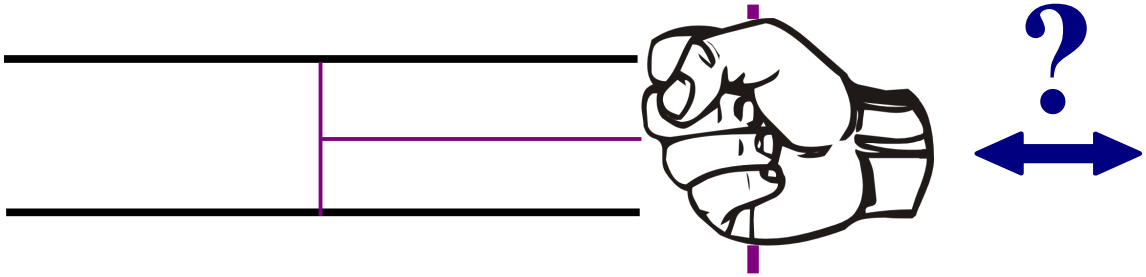
Mechanical noise from nacelle is NOT dominant!!!

The Physics of Sound Generation

There are no loudspeakers on wind turbine blades! Then...

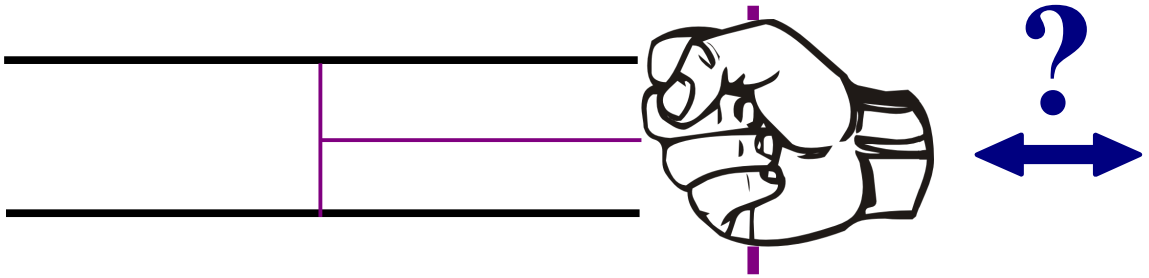
… WHO IS PUSHING?





The Physics of Sound Generation

… WHO IS PUSHING?

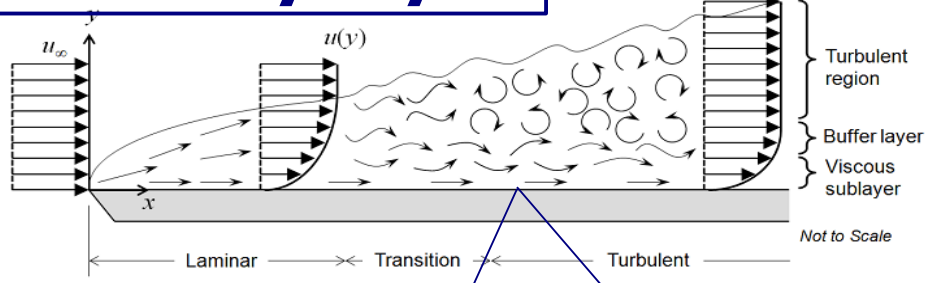


TURBULENCE!

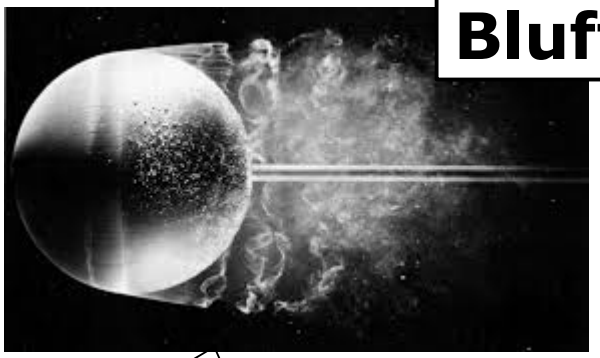
The Physics of Sound Generation

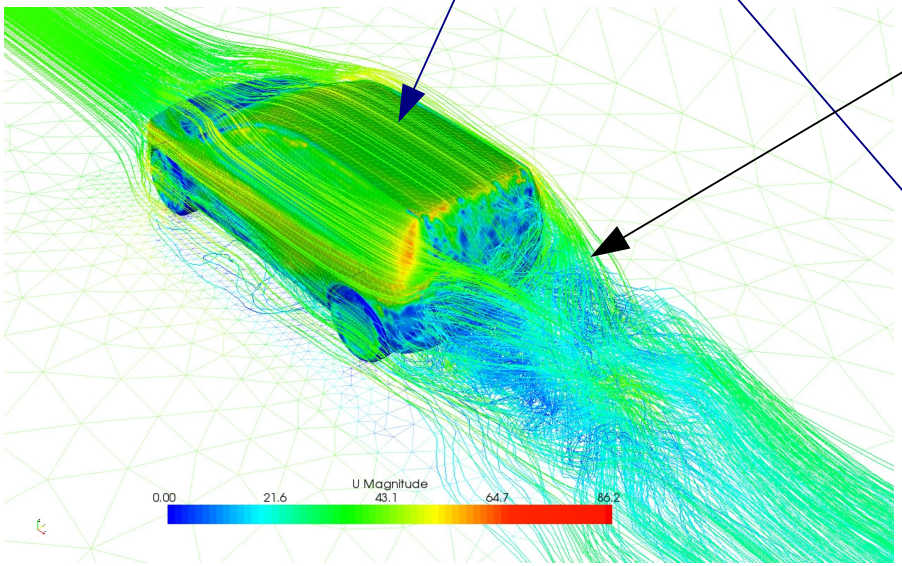
*What is **turbulence**?* Flow convection induces ***CHAOS***

Boundary layer

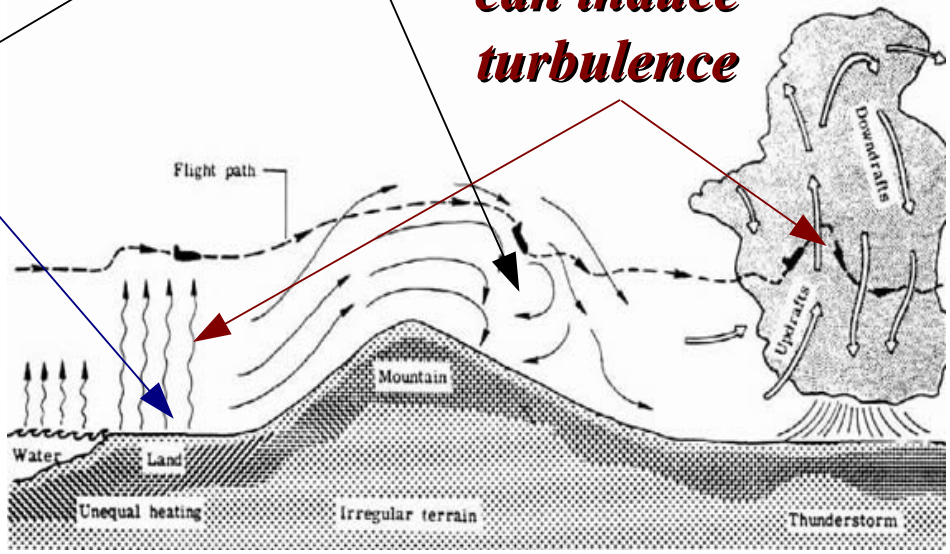


Bluff body



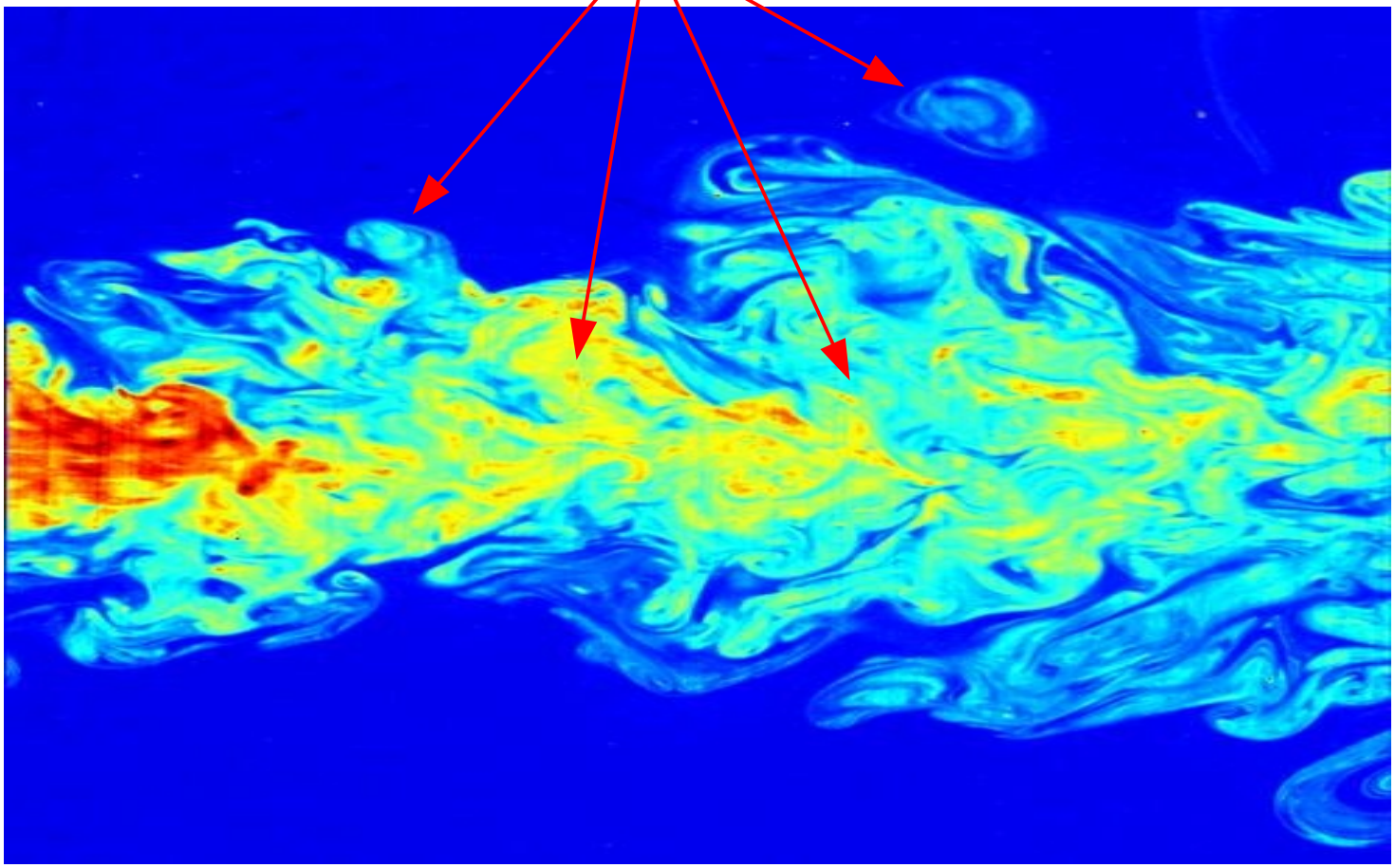


Thermal effects can induce turbulence



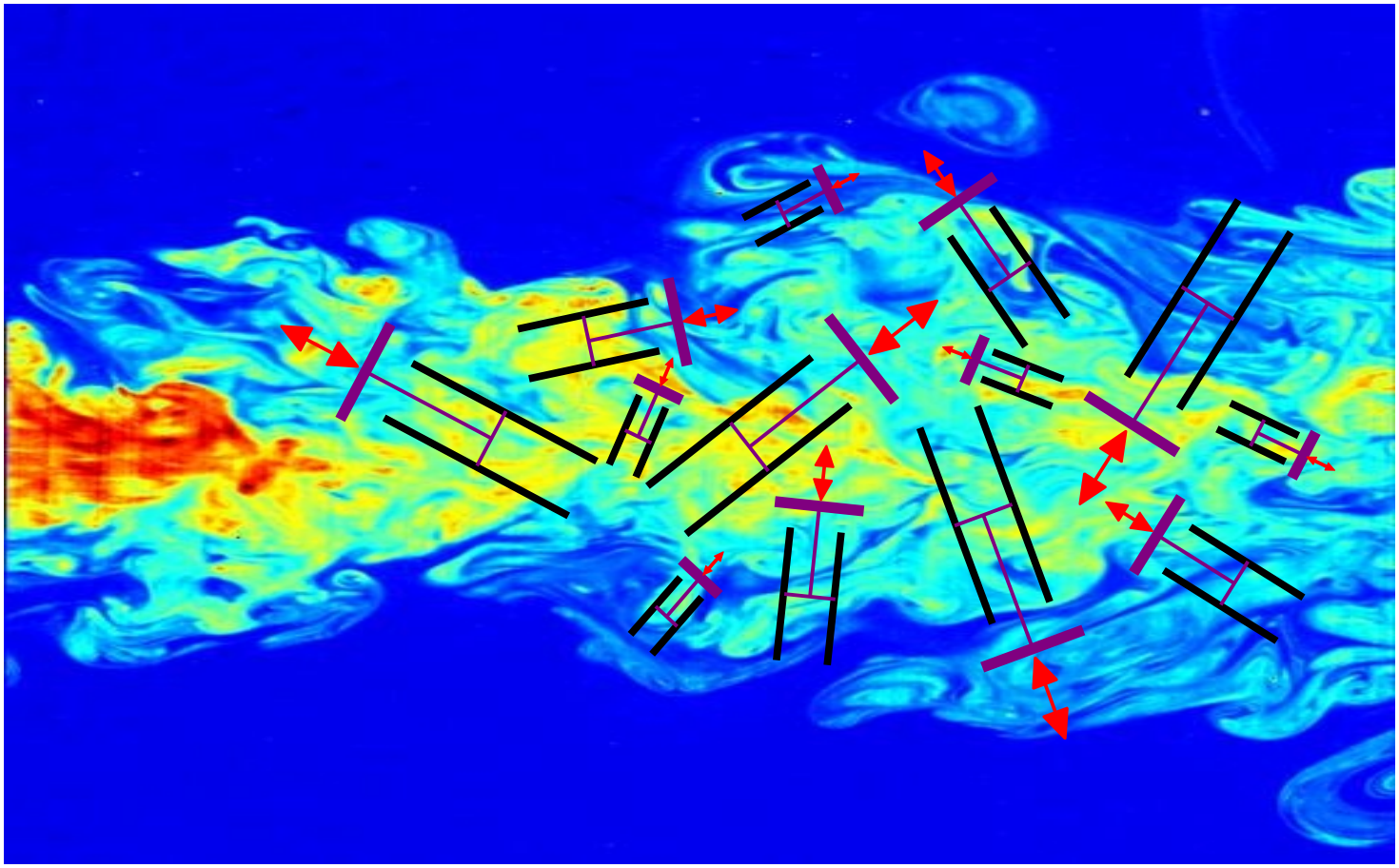
The Physics of Sound Generation

Flow turbulence is characterized by turbulent vortices!!!



The Physics of Sound Generation

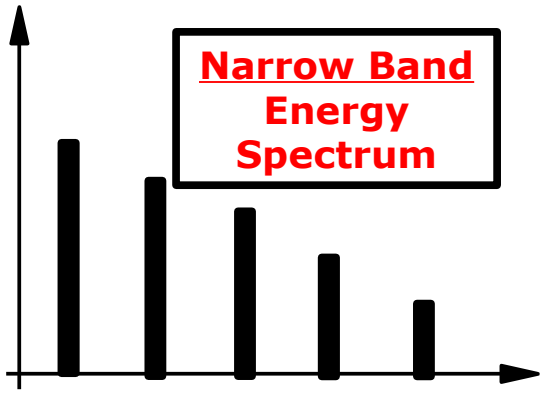
Turbulent vortices** are the pushers... they provide the **energy!



Generating *Aerodynamic Noise*

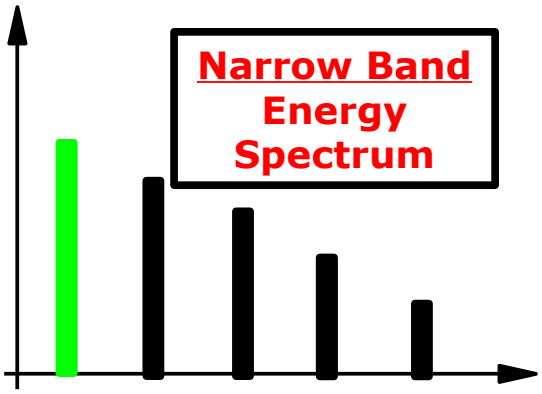
The Physics of Sound Generation

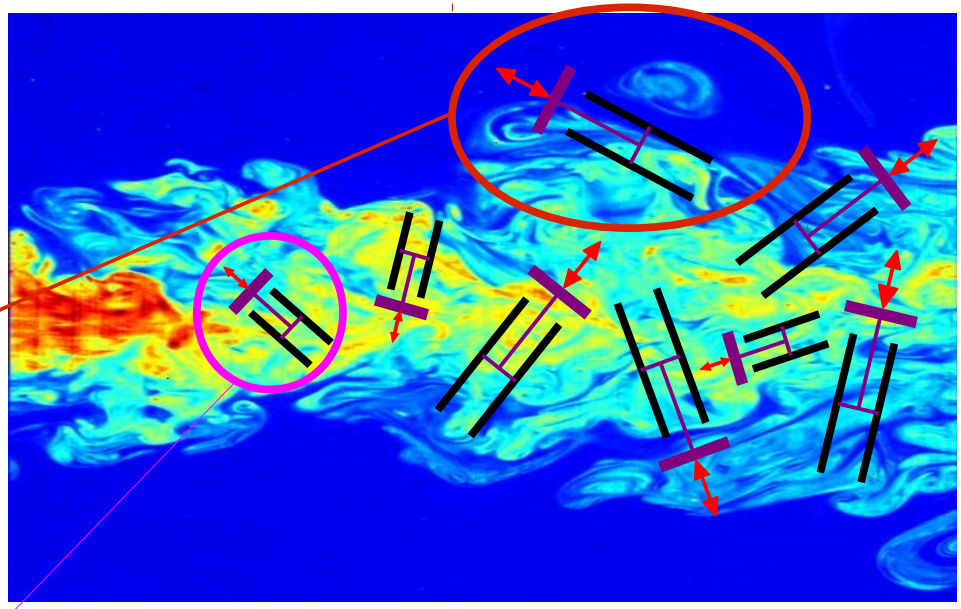
Aerodynamic noise is broadband:



The Physics of Sound Generation

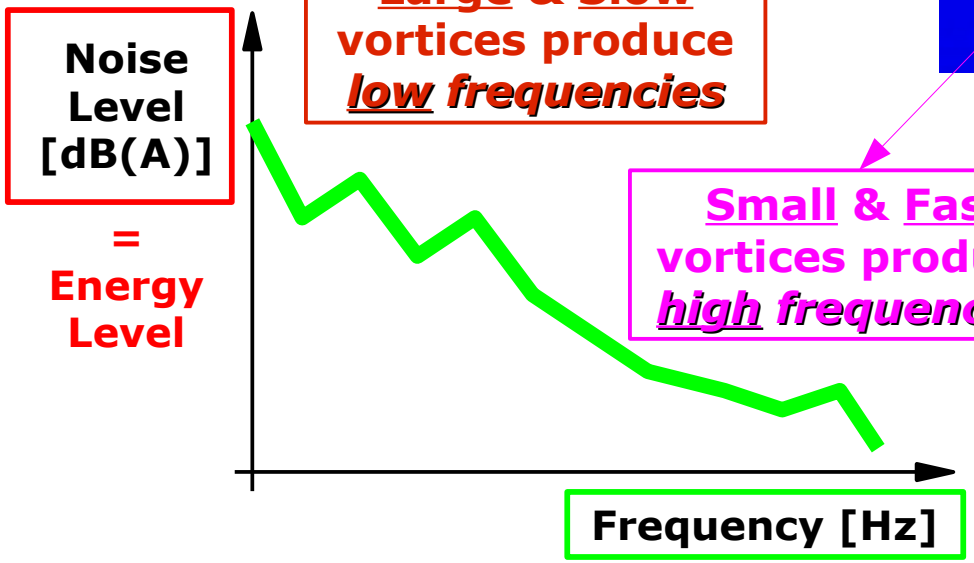
Aerodynamic noise is broadband:





Large & Slow
vortices produce
low frequencies

Small & Fast
vortices produce
high frequencies

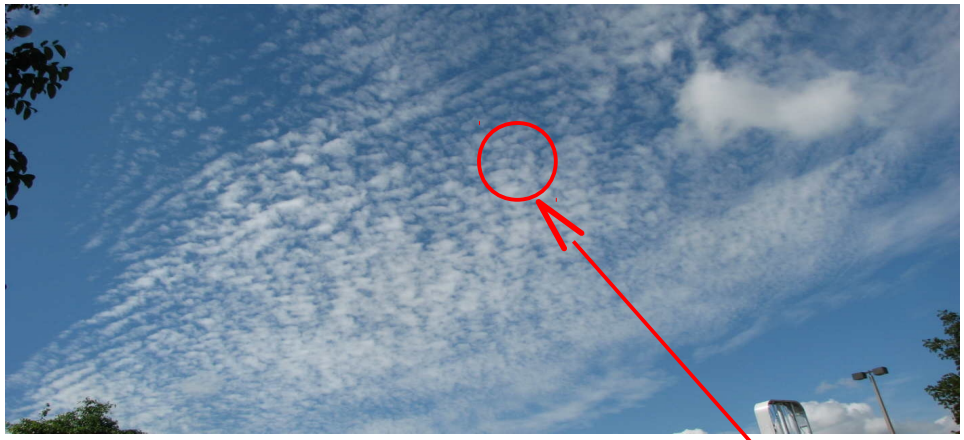


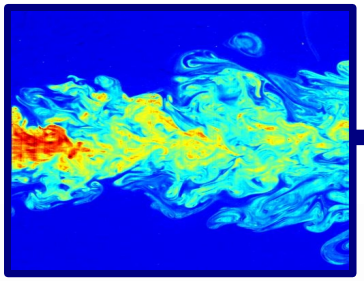
Broadband
Energy
Spectrum

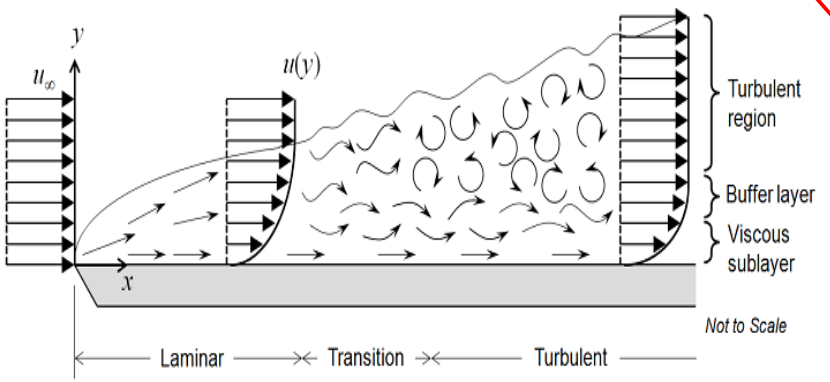
The Physics of Sound Generation

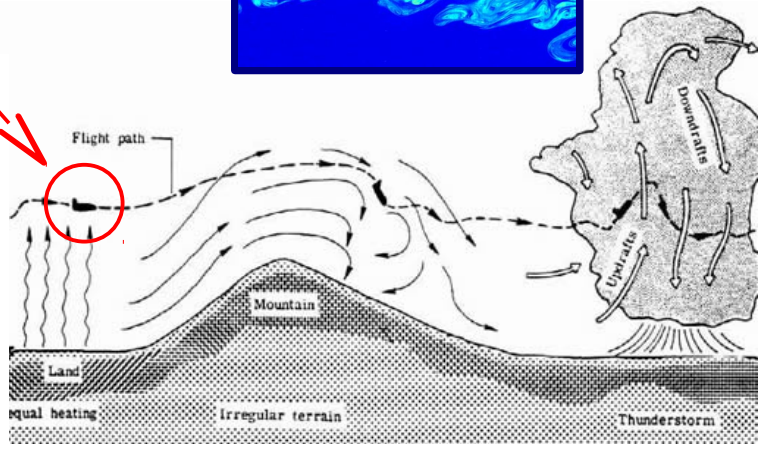
*Where is **turbulence** for wind turbine noise?*

1. From **atmosphere**





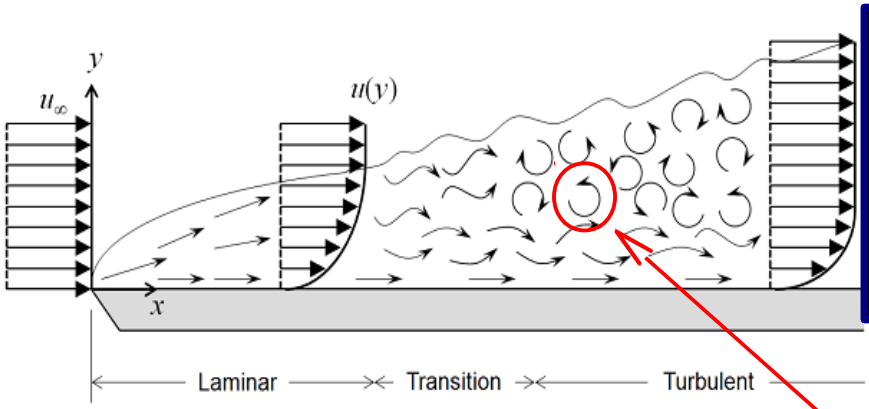


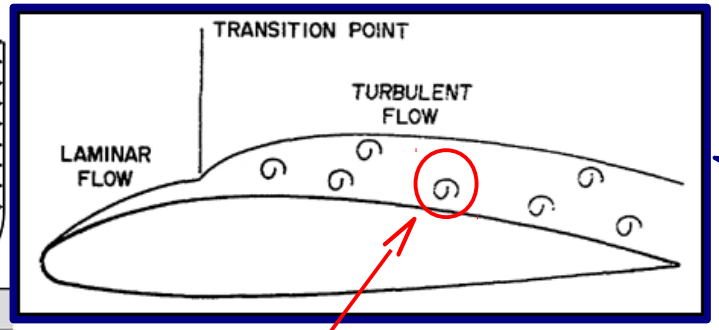


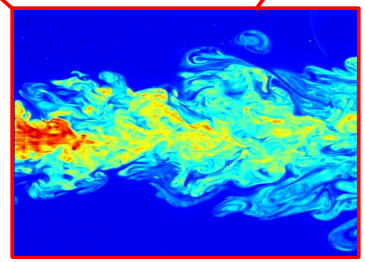
The Physics of Sound Generation

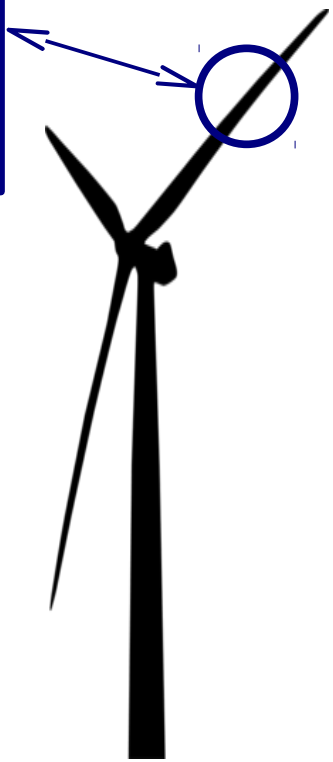
*Where is **turbulence** for wind turbine noise?*

2. Self-generated - Turbulent boundary layer









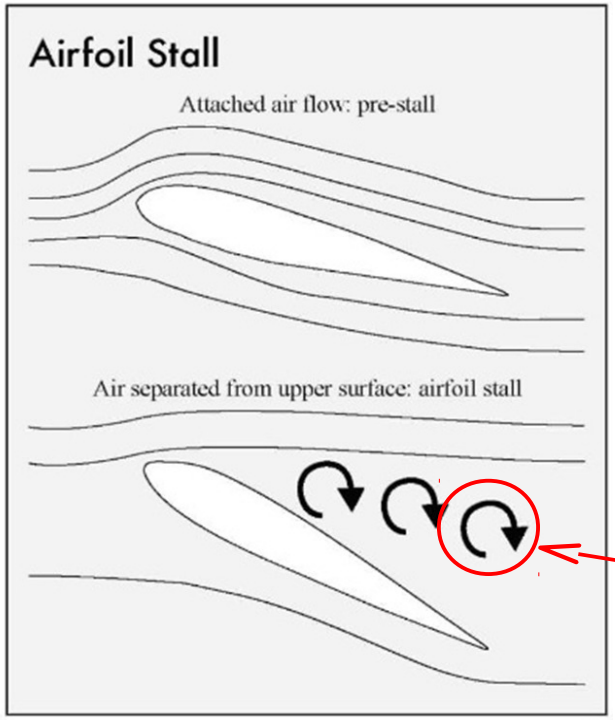
Airfoil relative speed near blade tip

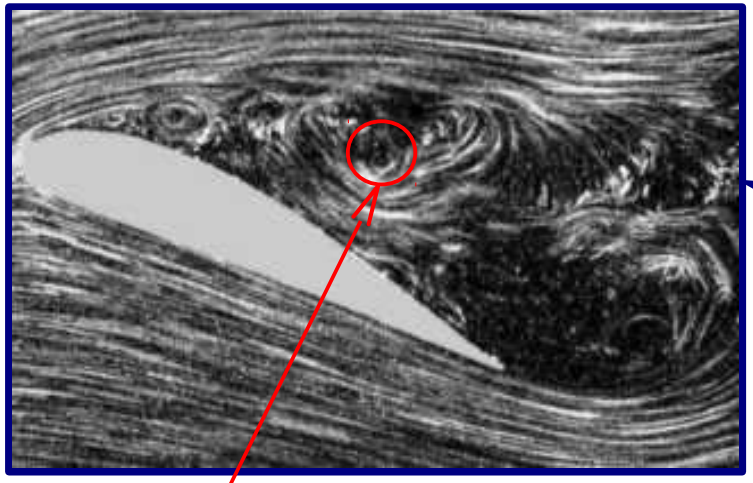
 # 300 km/h = 190 mile/h !!!

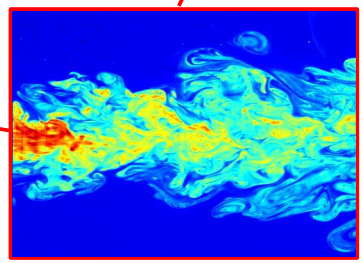
The Physics of Sound Generation

*Where is **turbulence** for wind turbine noise?*

3. Self-generated – Stalled flow





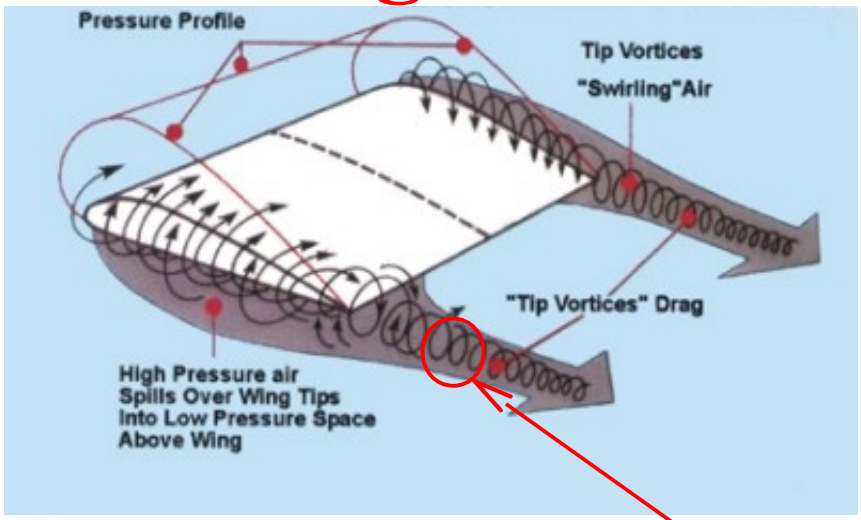


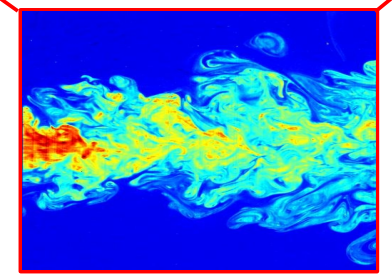
For high angles of attack

The Physics of Sound Generation

*Where is **turbulence** for a wind turbine?*

4. Self-generated - Tip vortex



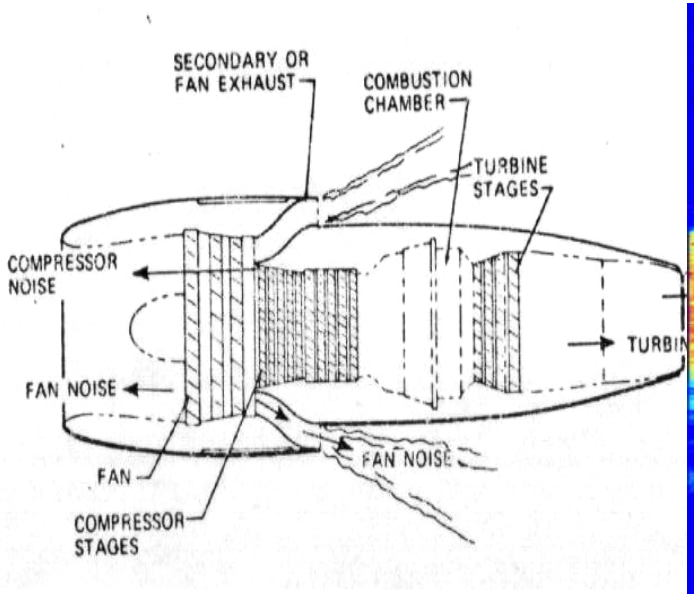


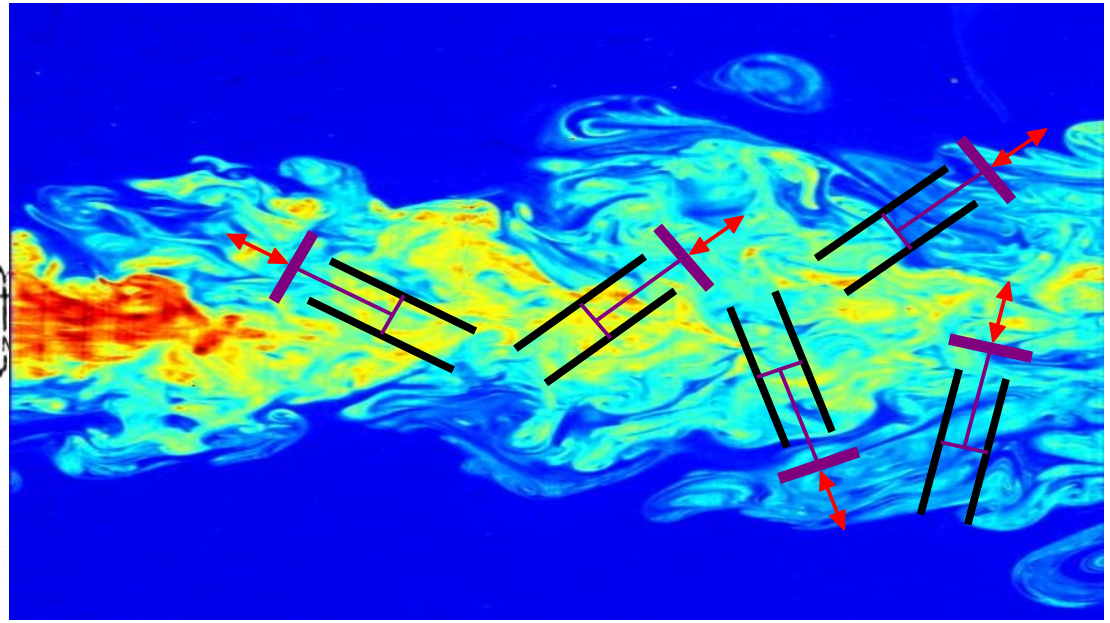
Blade tip speed # 300 km/h = 190 mile/h!

The Physics of Sound Generation

Turbulent vortices are the pushers...

BUT it is bad quality stuff: *Not efficient!*



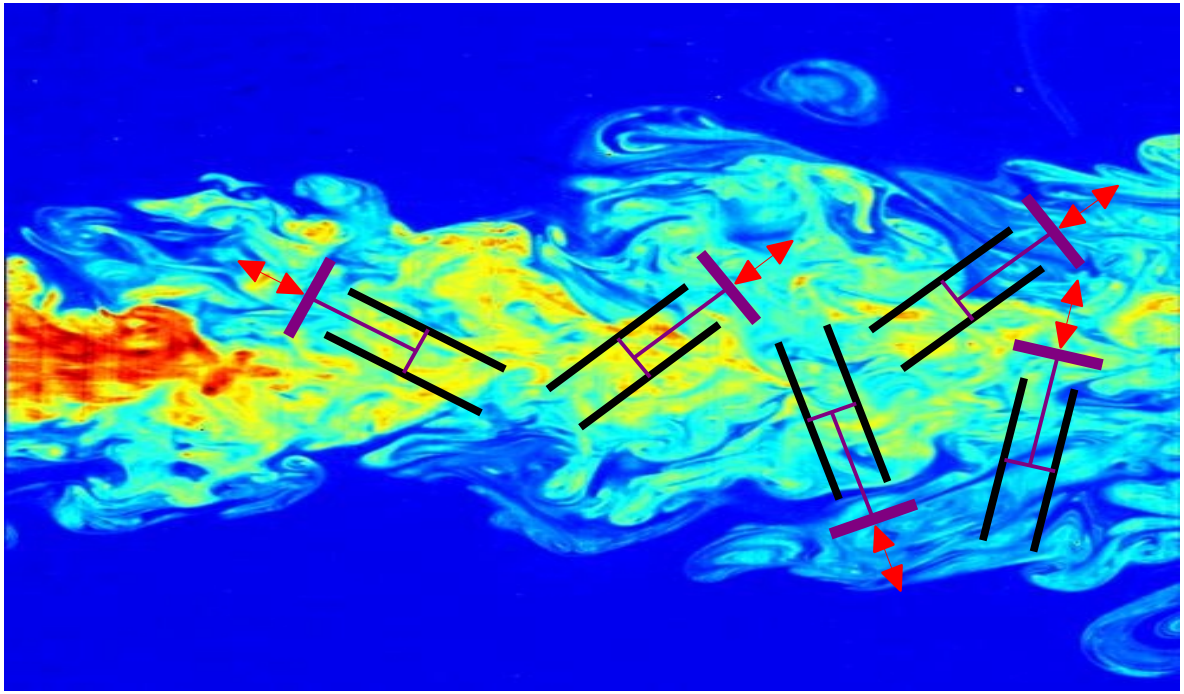


***Jet engine noise...** is helped by **combustion** adding **ENERGY** and **SPEED** to the turbulent flow*

The Physics of Sound Generation

Why turbulence alone is not efficient?

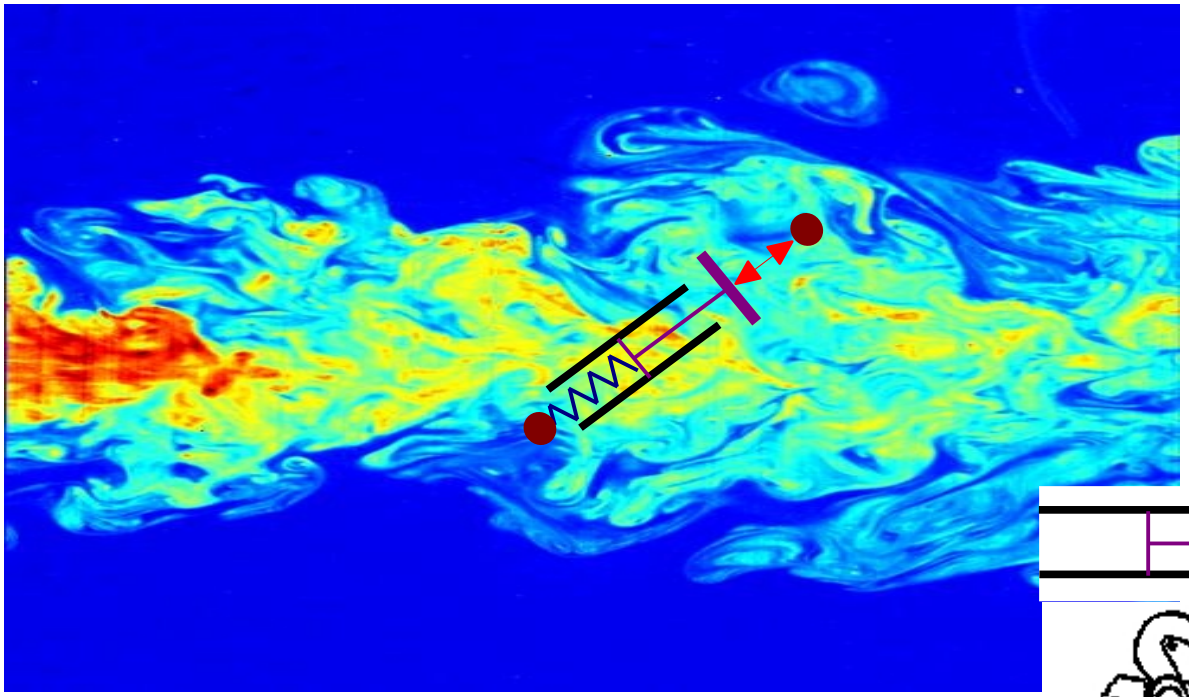
Turbulent vortices are pushing... *air against air!!*



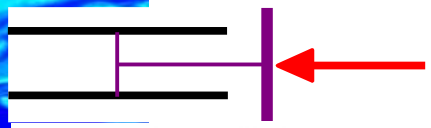
Analogy:
like pushing something in space..

The Physics of Sound Generation

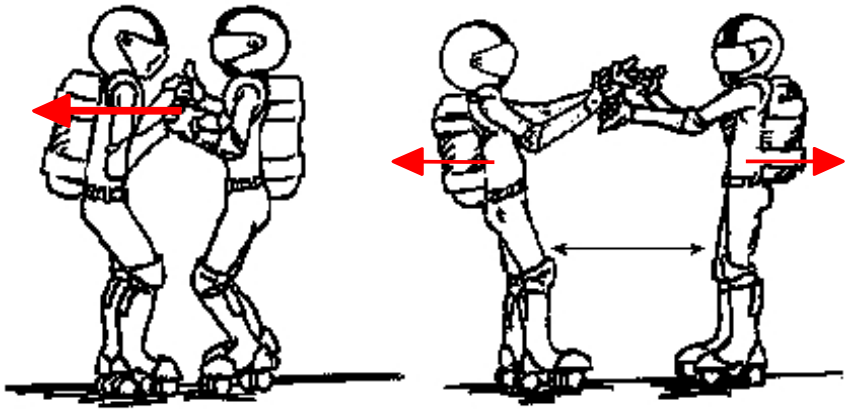
Turbulent vortices are pushing... air against air!!



Analogy:

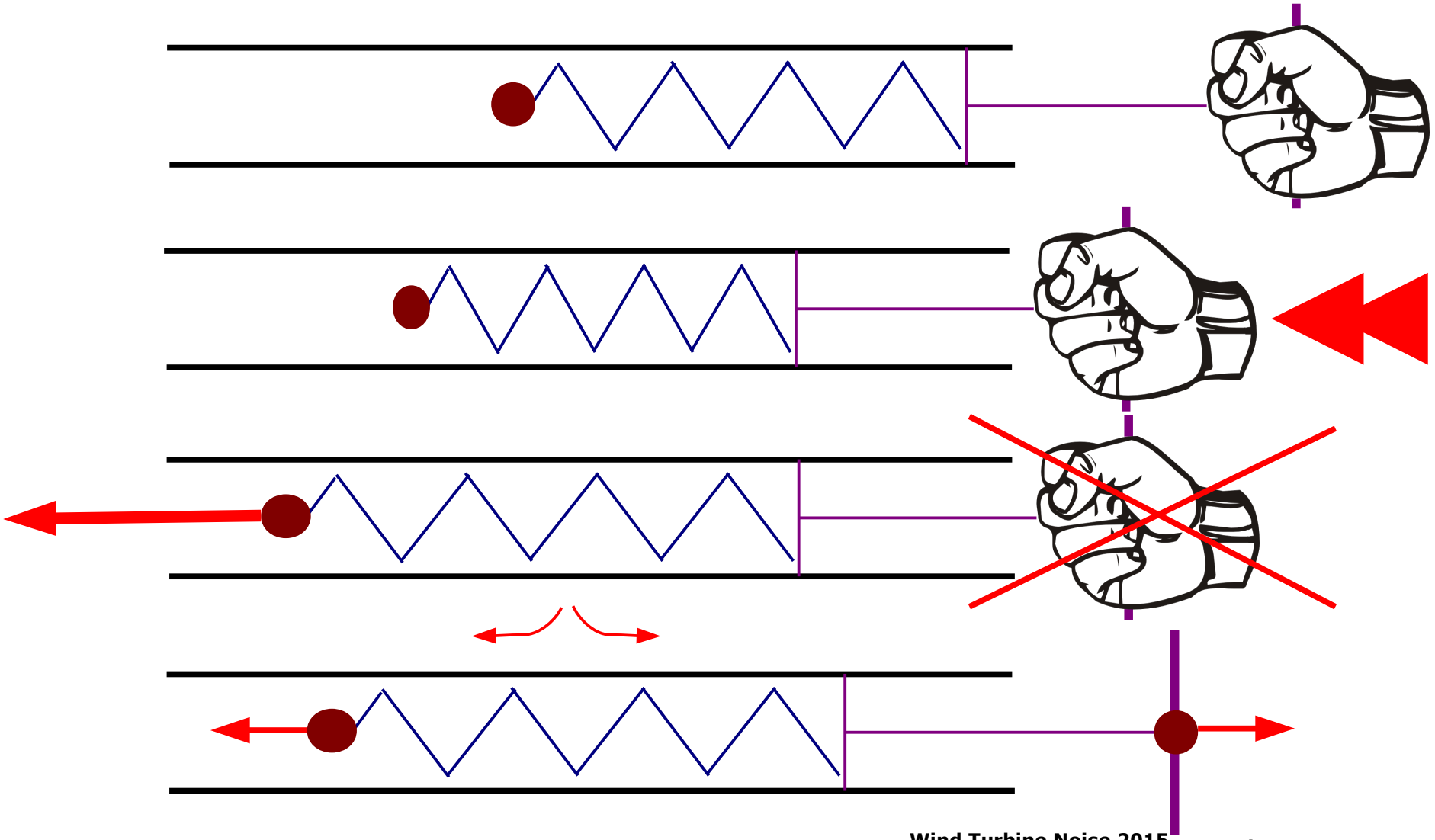


Push



The Physics of Sound Generation

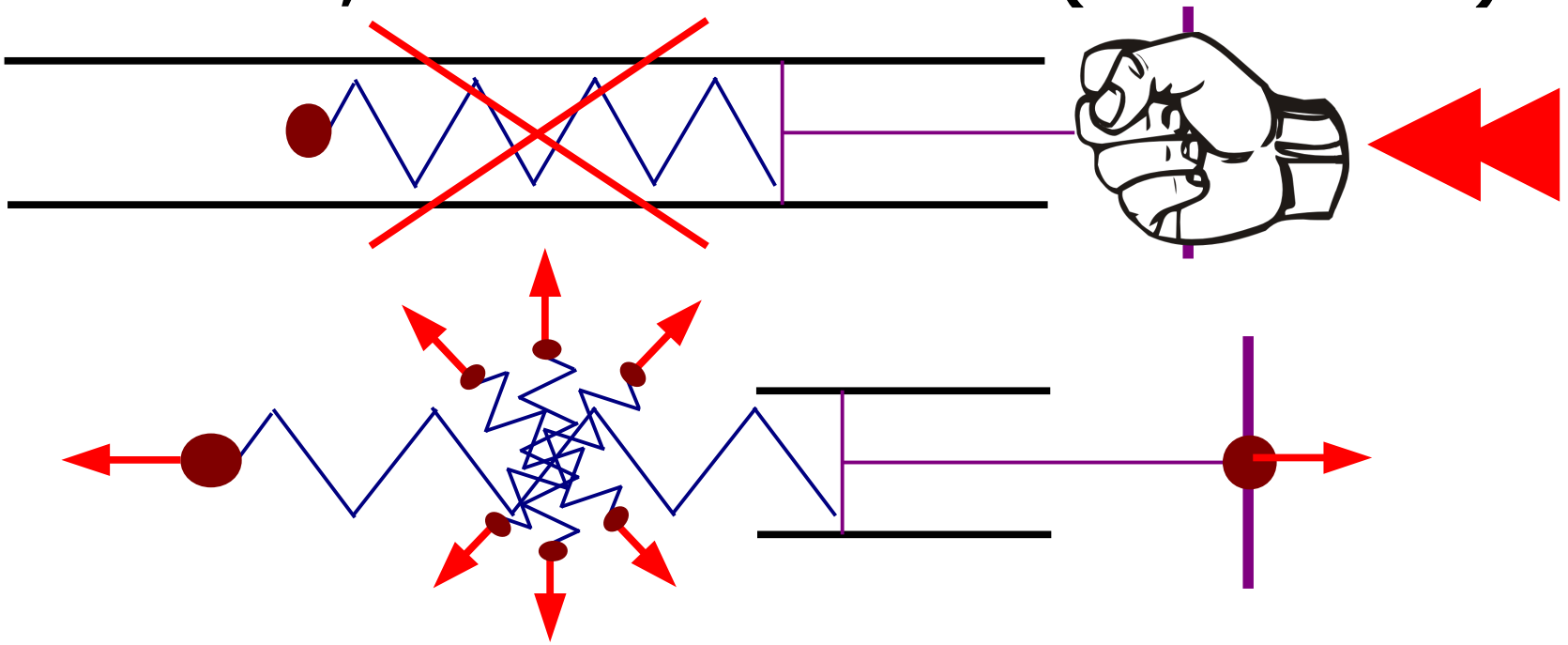
Analogy: ➢ **Air mass+spring against mass+spring**



The Physics of Sound Generation

Analogy: ➢ **Air mass+spring against mass+spring**

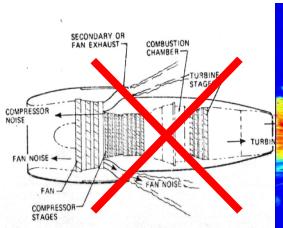
Turbulent vortices push in <u>one direction</u>, but energy redistributed not only in one direction, but in *all directions* (air medium)

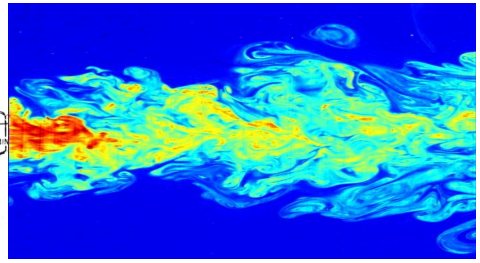


Therefore <u>turbulence alone</u> is *<u>VERY inefficient</u>* to produce noise!

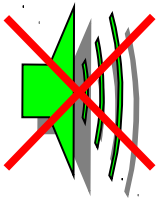
The Physics of Sound Generation

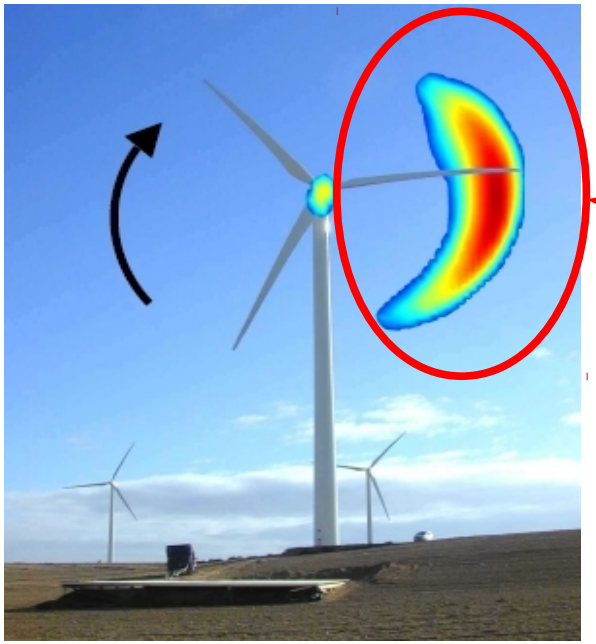
No combustion





No loudspeaker on blades...





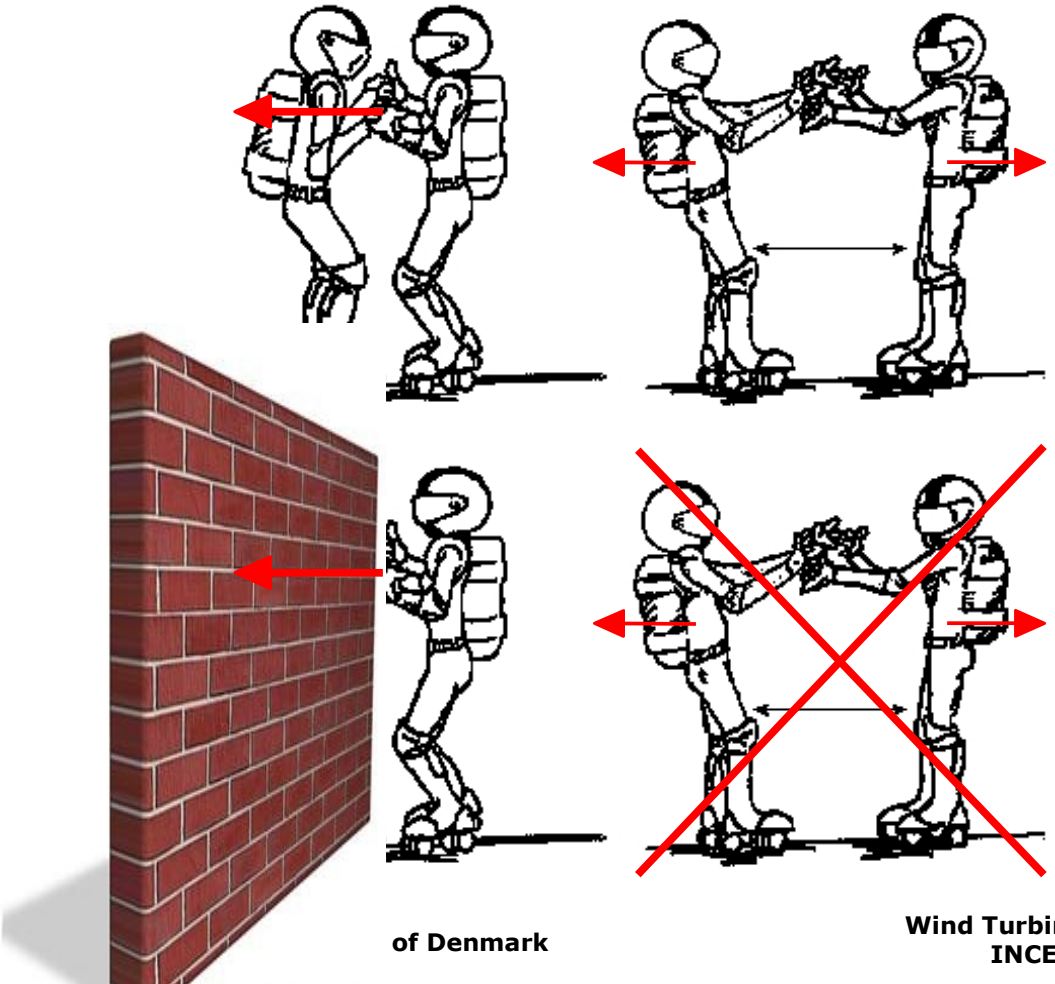
Then.. how is wind turbine noise generated?

There are hidden loudspeakers!!!

The Physics of Sound Generation

One hidden loudspeaker...

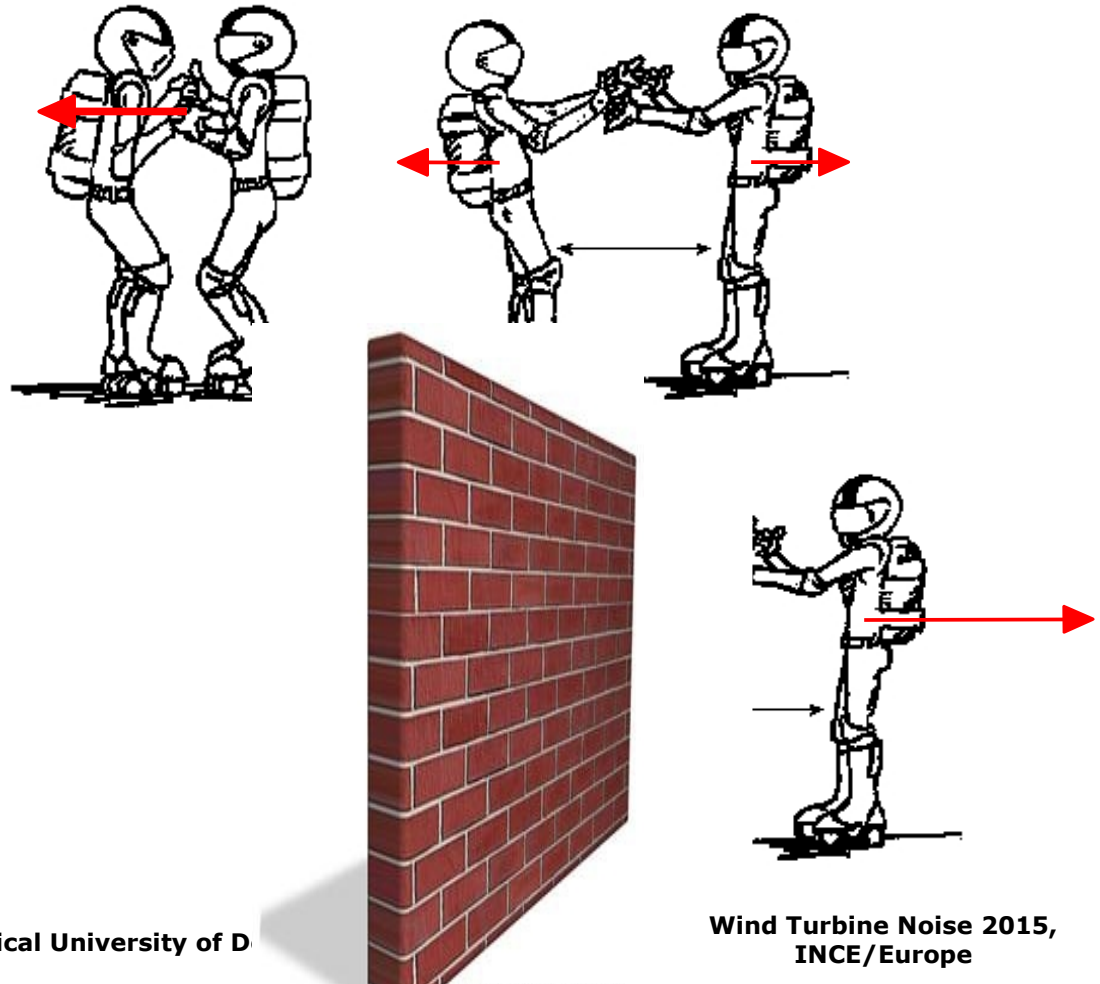
... is the blade *hard surface*!



The Physics of Sound Generation

One hidden loudspeaker...

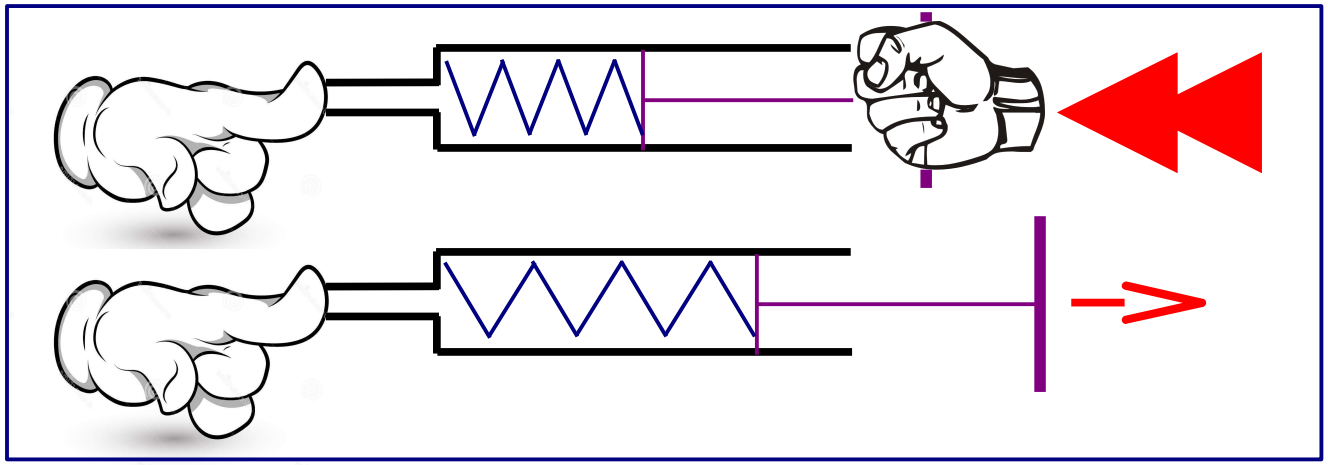
... is the blade *hard surface*!

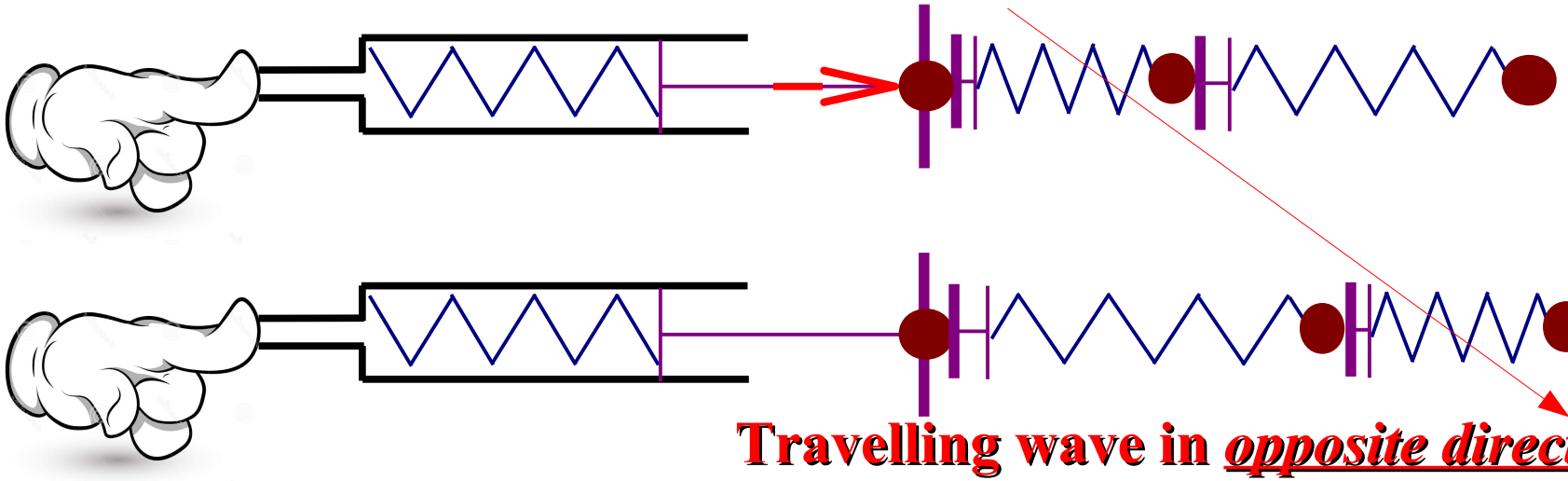


The Physics of Sound Generation

Analogy:

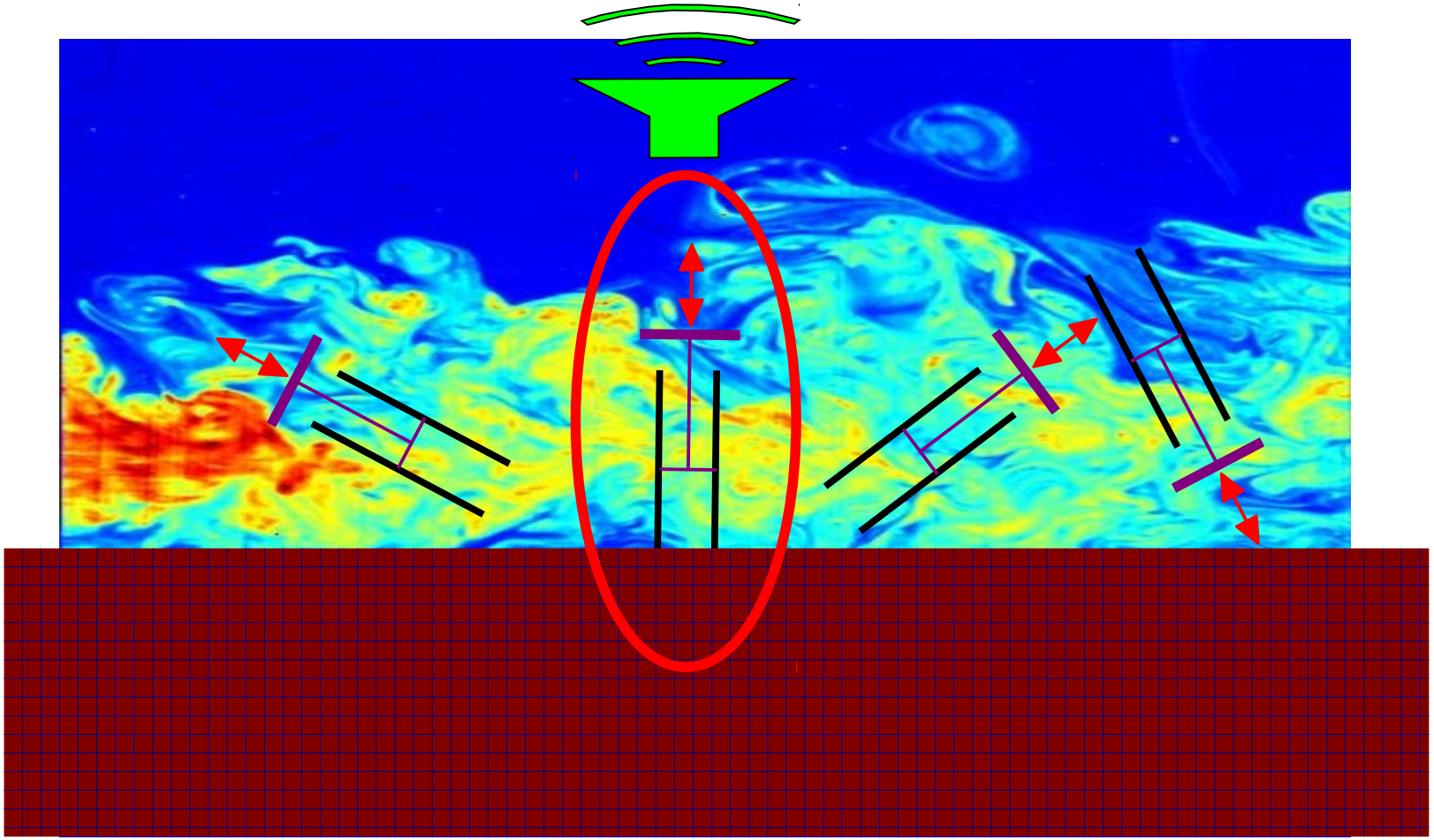
- The **AIR** is ***compressible*** = acts as a ***SPRING***!





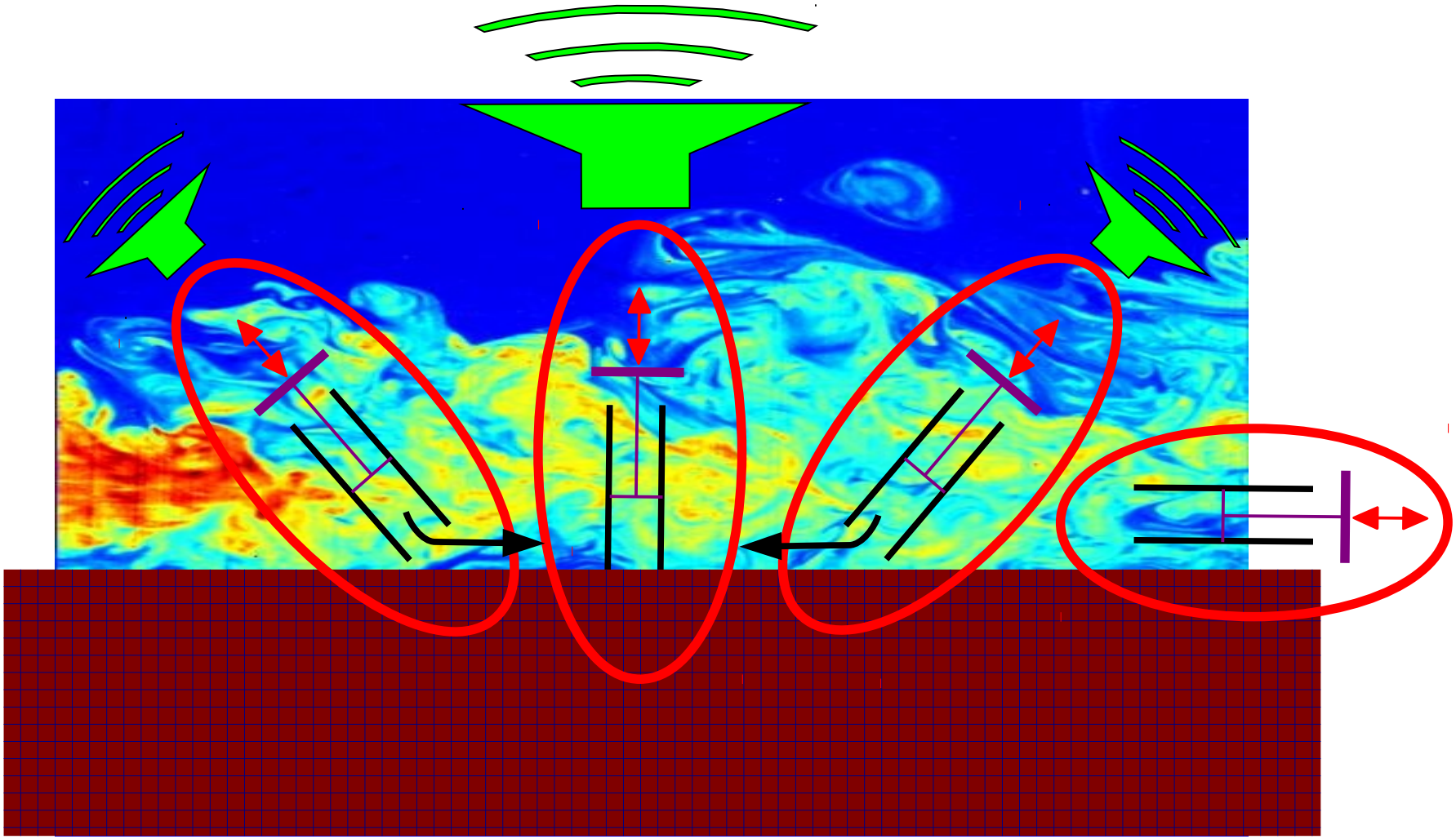
The Physics of Sound Generation

Turbulent vortices pushing against the wall do make more noise!!!



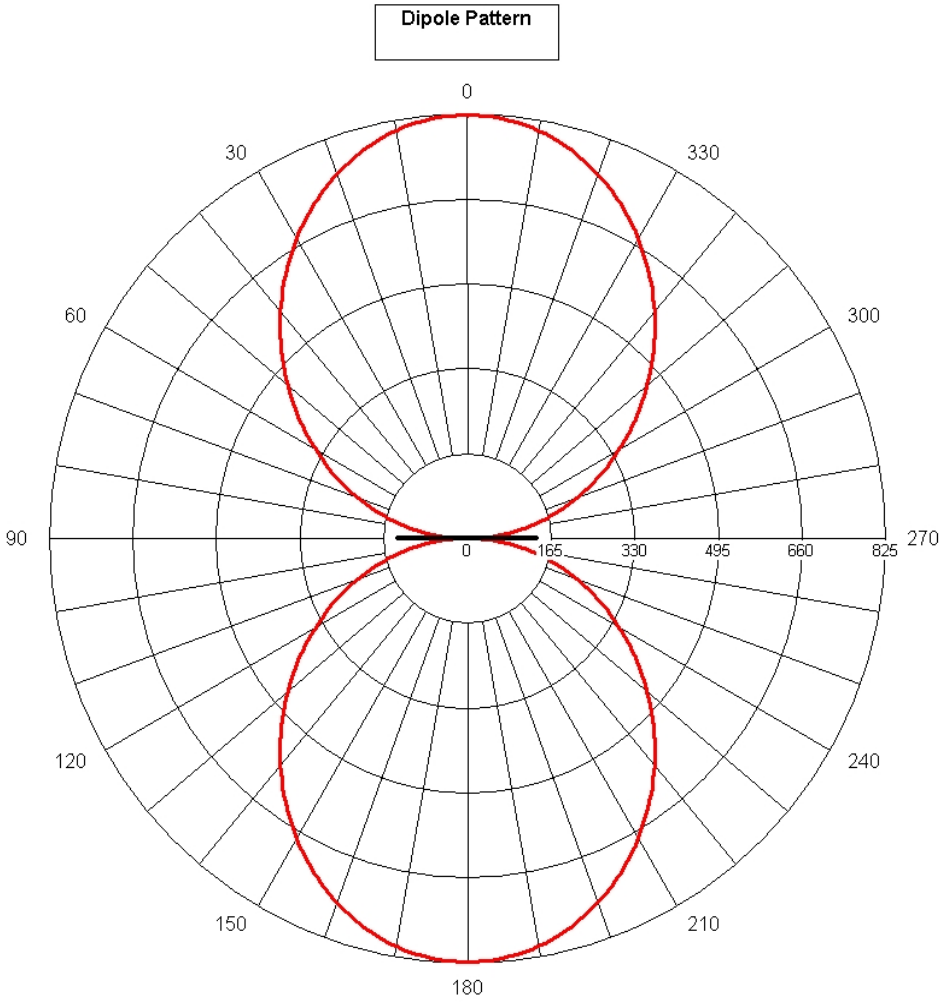
The Physics of Sound Generation

Explains directivity effects:



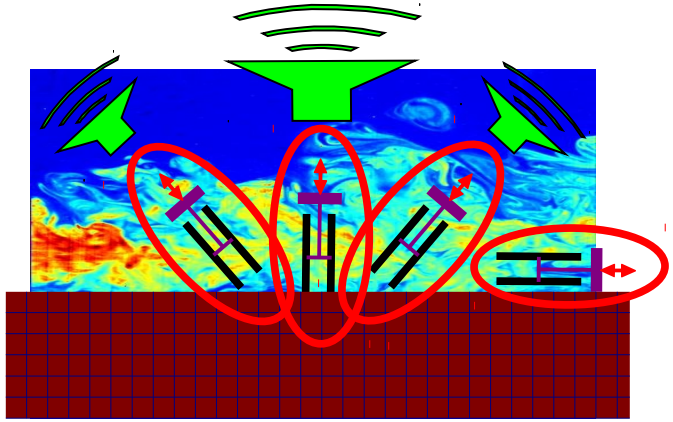
The Physics of Sound Generation

Explains directivity effects:

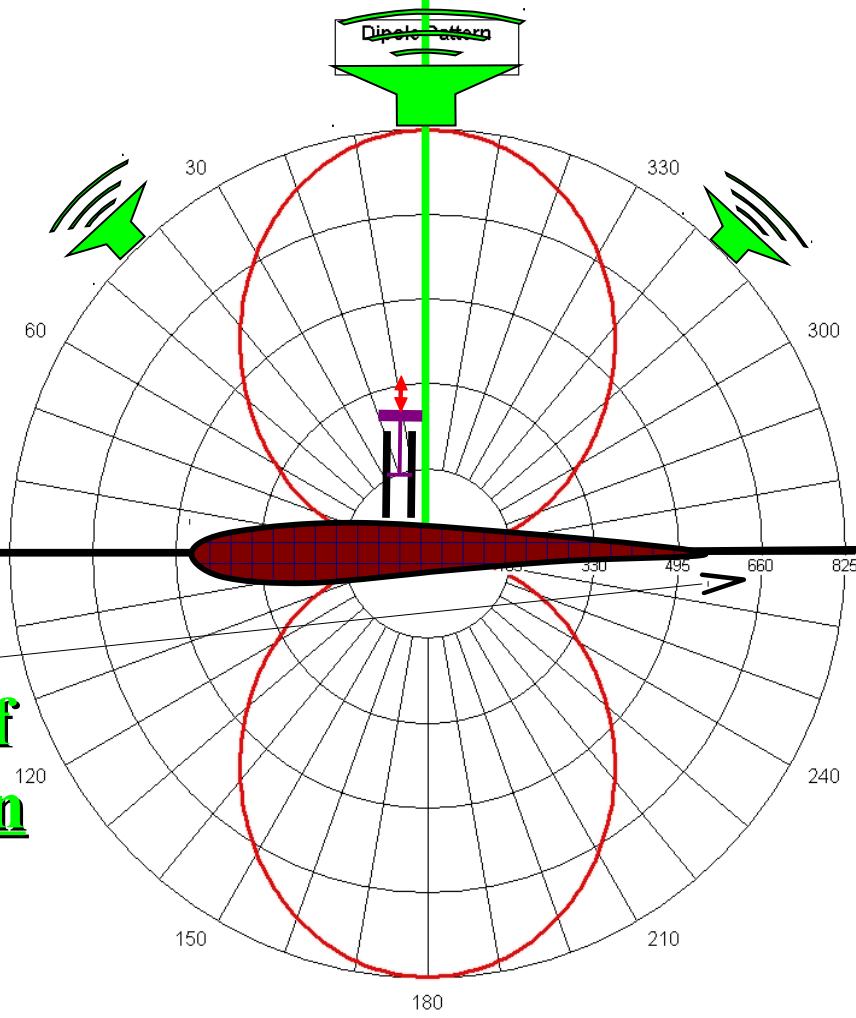


The Physics of Sound Generation

Explains directivity effects:



Direction of maximum radiation



Silence zone

Silence zone

Directions of null radiation

The Physics of Sound Generation

Aerodynamic noise source mechanisms

Two mechanisms were identified:

1. **Turbulence alone** … *Inefficient* ~ M_a^8*!*
2. **Hard surfaces** … *Not efficient either* ~ M_a^6*!*

Still cannot explain wind turbines noise generation!?

The Physics of Sound Generation

Aerodynamic noise source mechanisms

Two mechanisms were identified:

1. **Turbulence alone** … *Inefficient!*
2. **Hard surfaces** … *Not very efficient either!*

Still cannot explain why WT noise generation!?

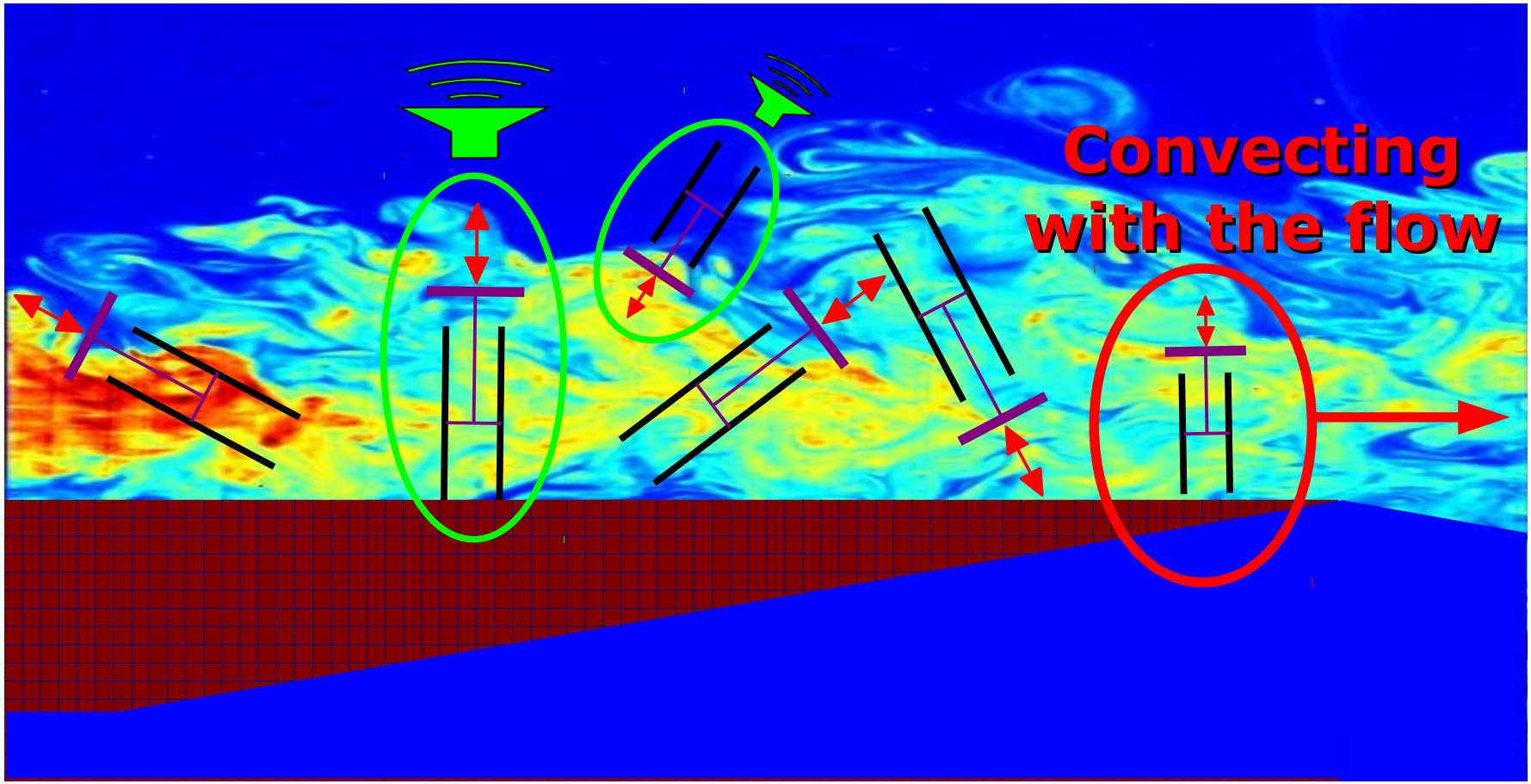
The really efficient noise source mechanism:

EDGE SCATTERING NOISE!!!

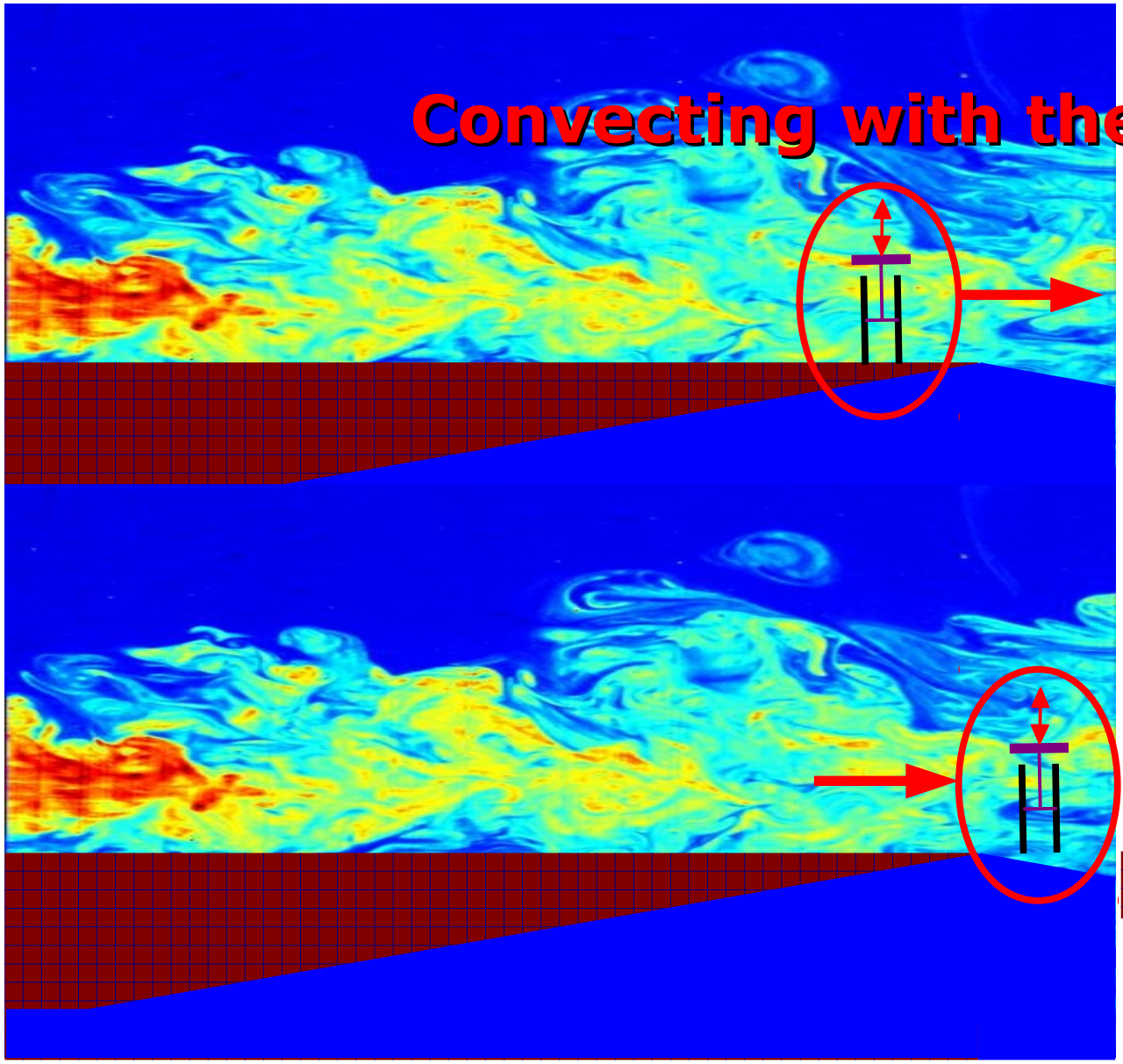
The Physics of Sound Generation

Trailing edge noise

= Scattering phenomenon



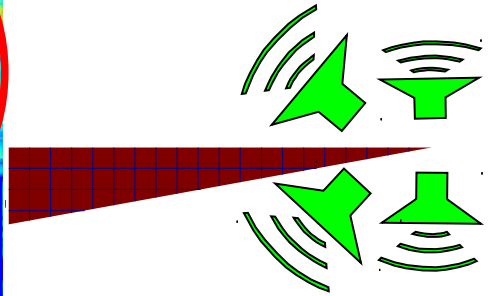
The Physics of Sound Generation



Trailing edge

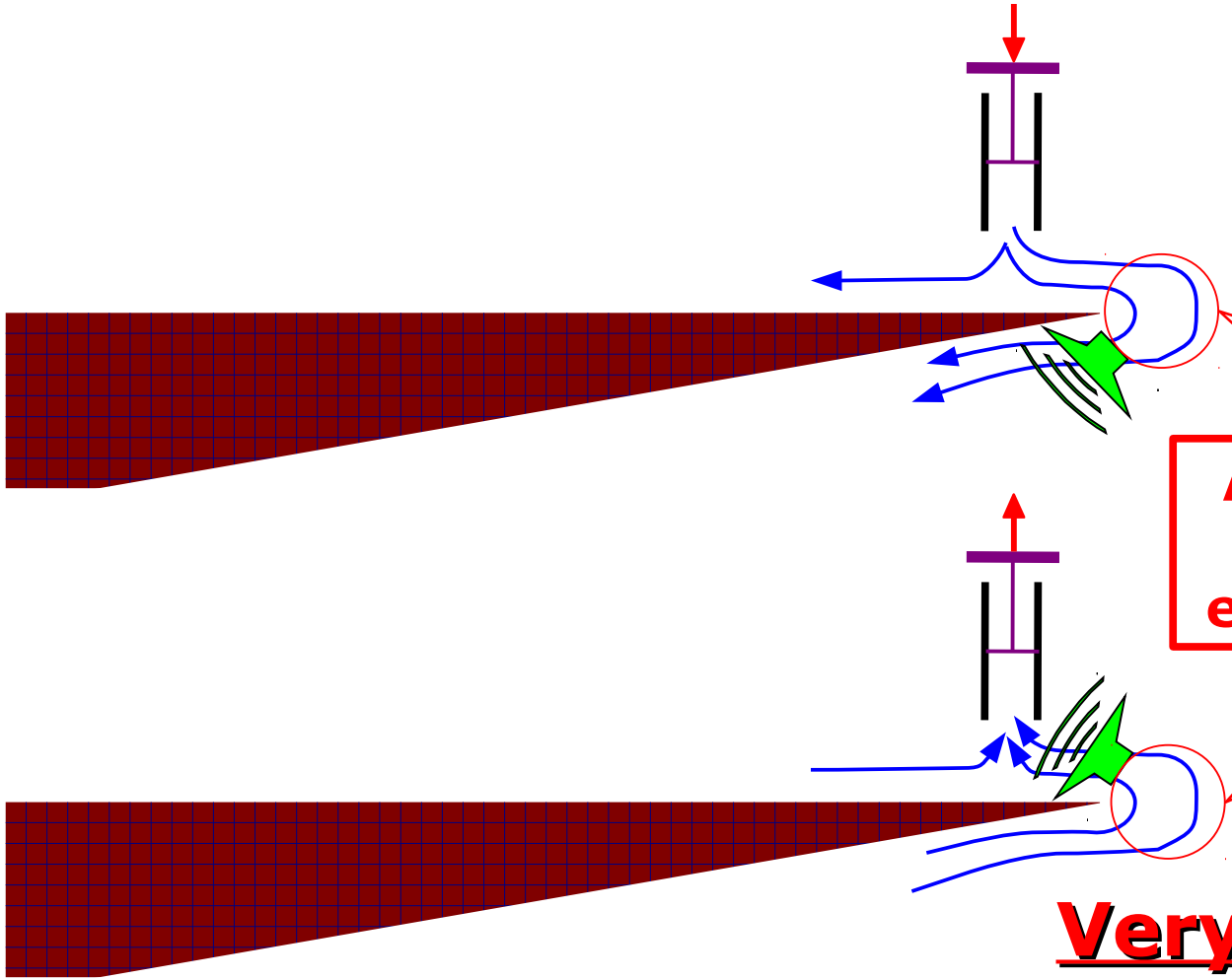
scattering

noise



The Physics of Sound Generation

Trailing edge scattering noise

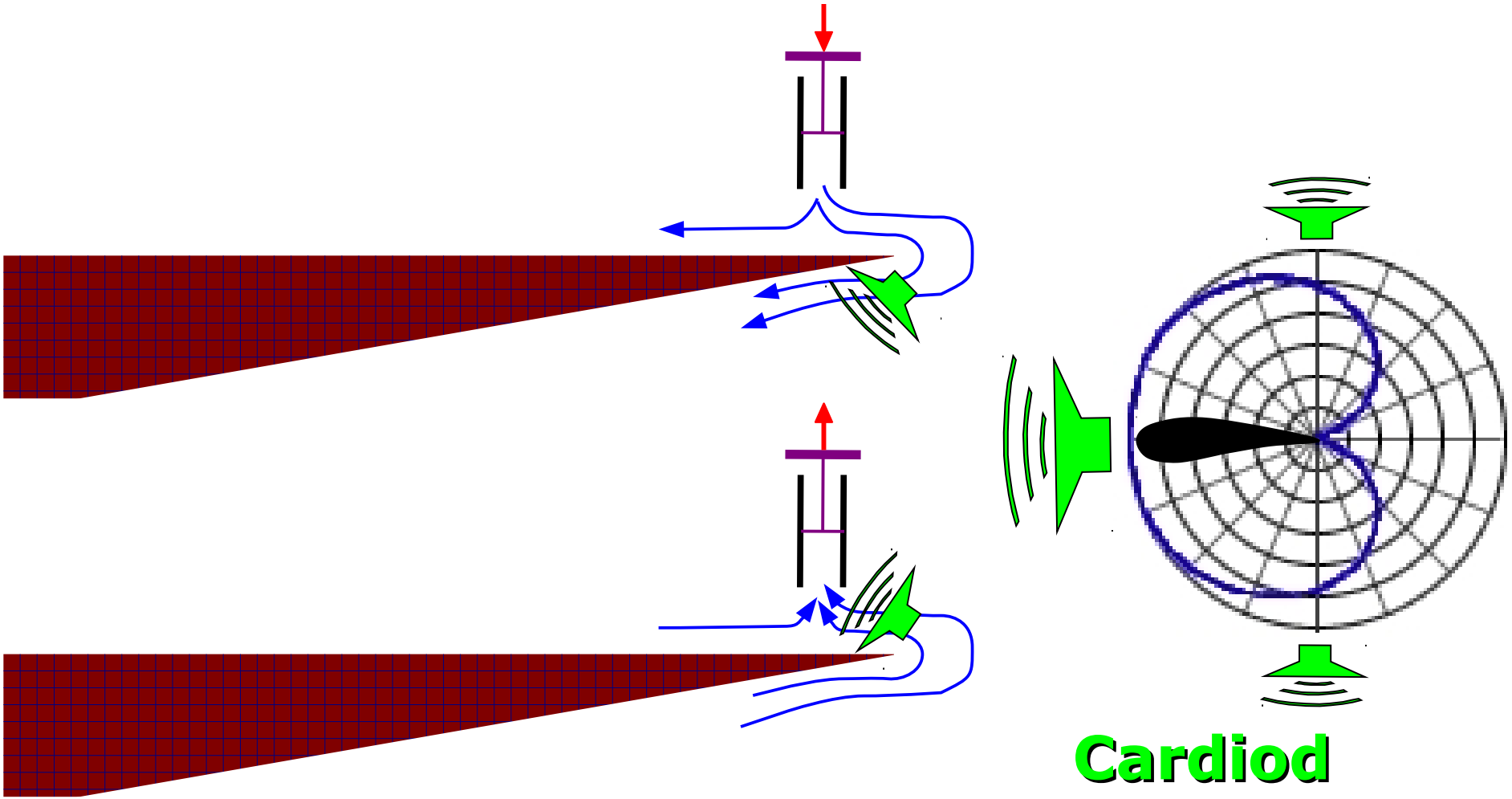


Air accelerated due to edge singularity

Very efficient noise generator!!

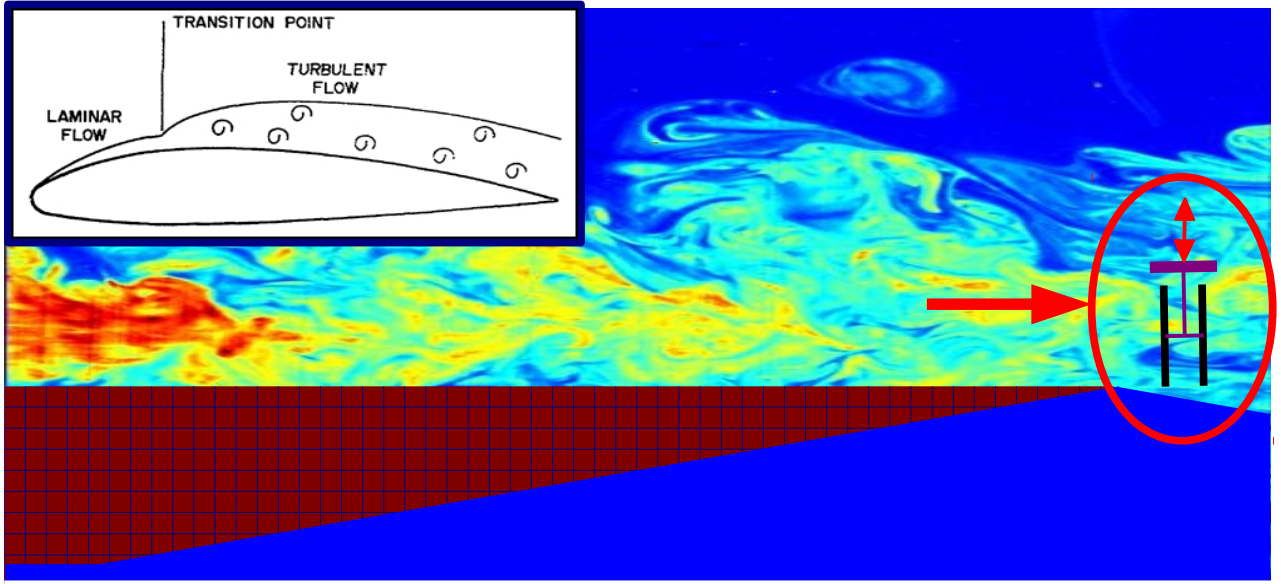
The Physics of Sound Generation

Trailing edge scattering noise

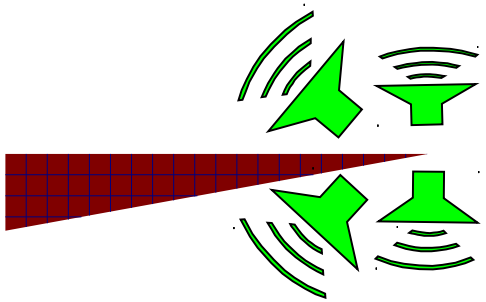


Cardiod directicity pattern

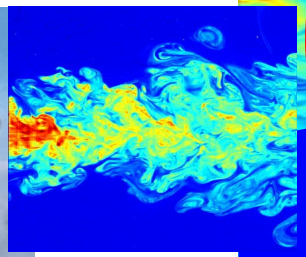
The Physics of Sound Generation

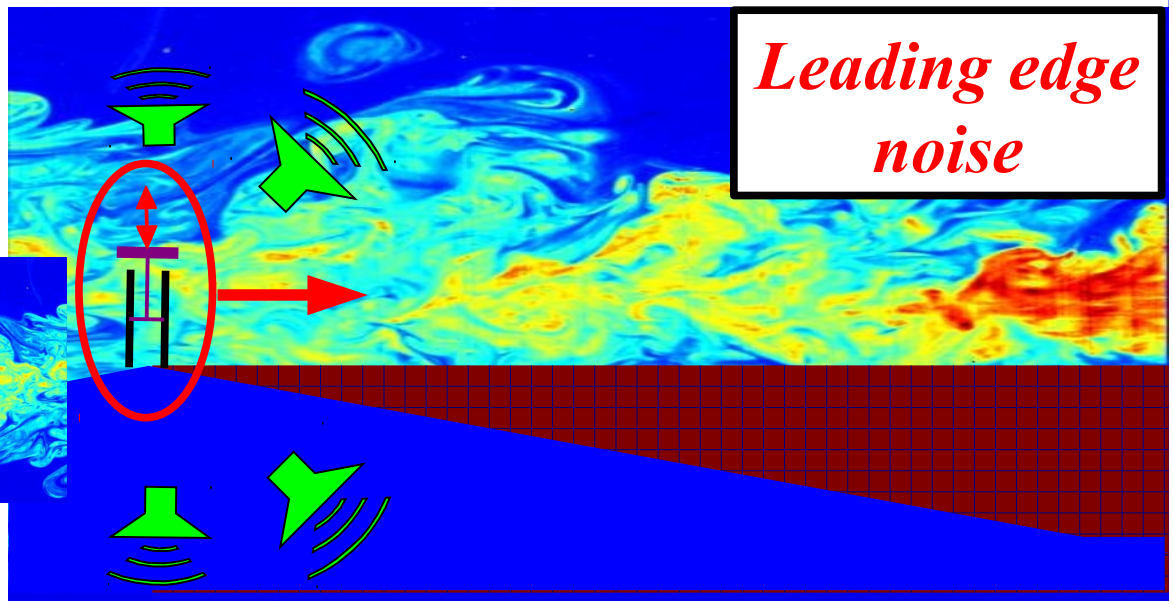


Trailing edge noise



Turbulent Inflow Noise





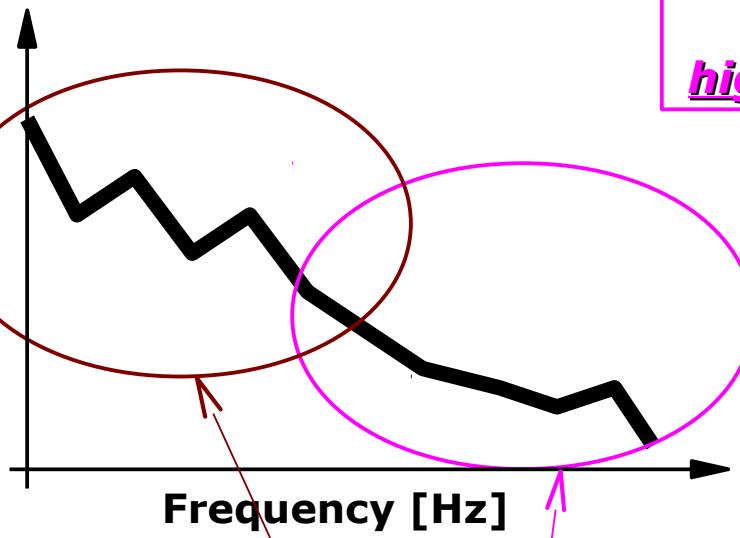
Leading edge noise

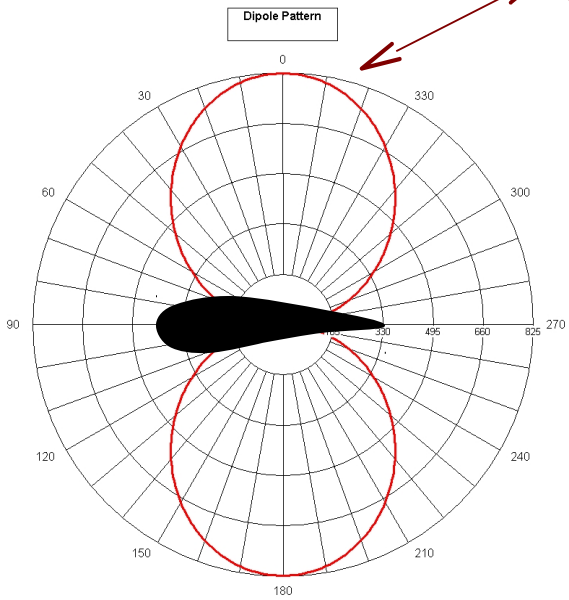
The Physics of Sound Generation

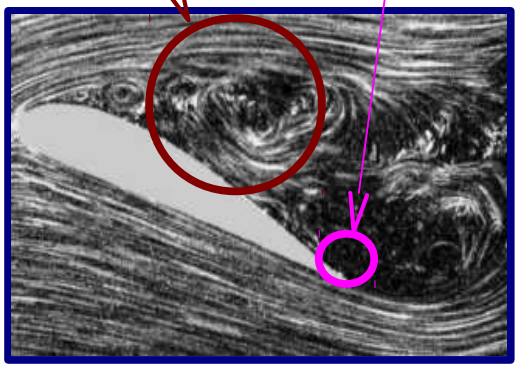
Directivity of stall noise

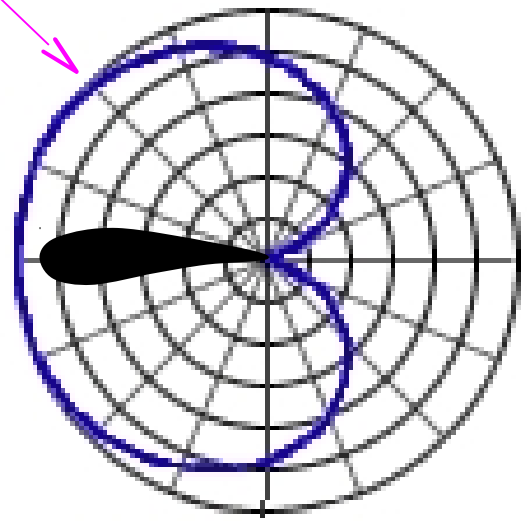
Large vortices produce *low frequencies*

Small vortices produce *high frequencies*









The Physics of Sound Generation

Wind turbine noise source mechanisms:

Four main mechanisms were identified:

1. **Trailing edge noise**

   From self-generated turbulent boundary layer

2. **Leading edge noise**

   From atmospheric turbulence

3. **Stall Noise**

   From separated flow over airfoil at high AoA

4. **Tip Noise**

   Still unclear if tip vortex interacts with tip or edge?!

Outline

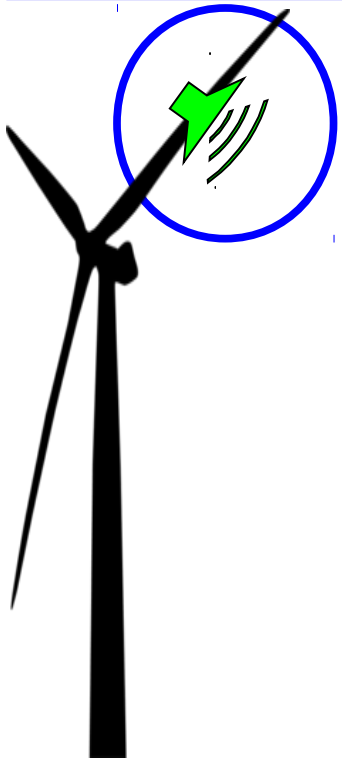
Two main parts:

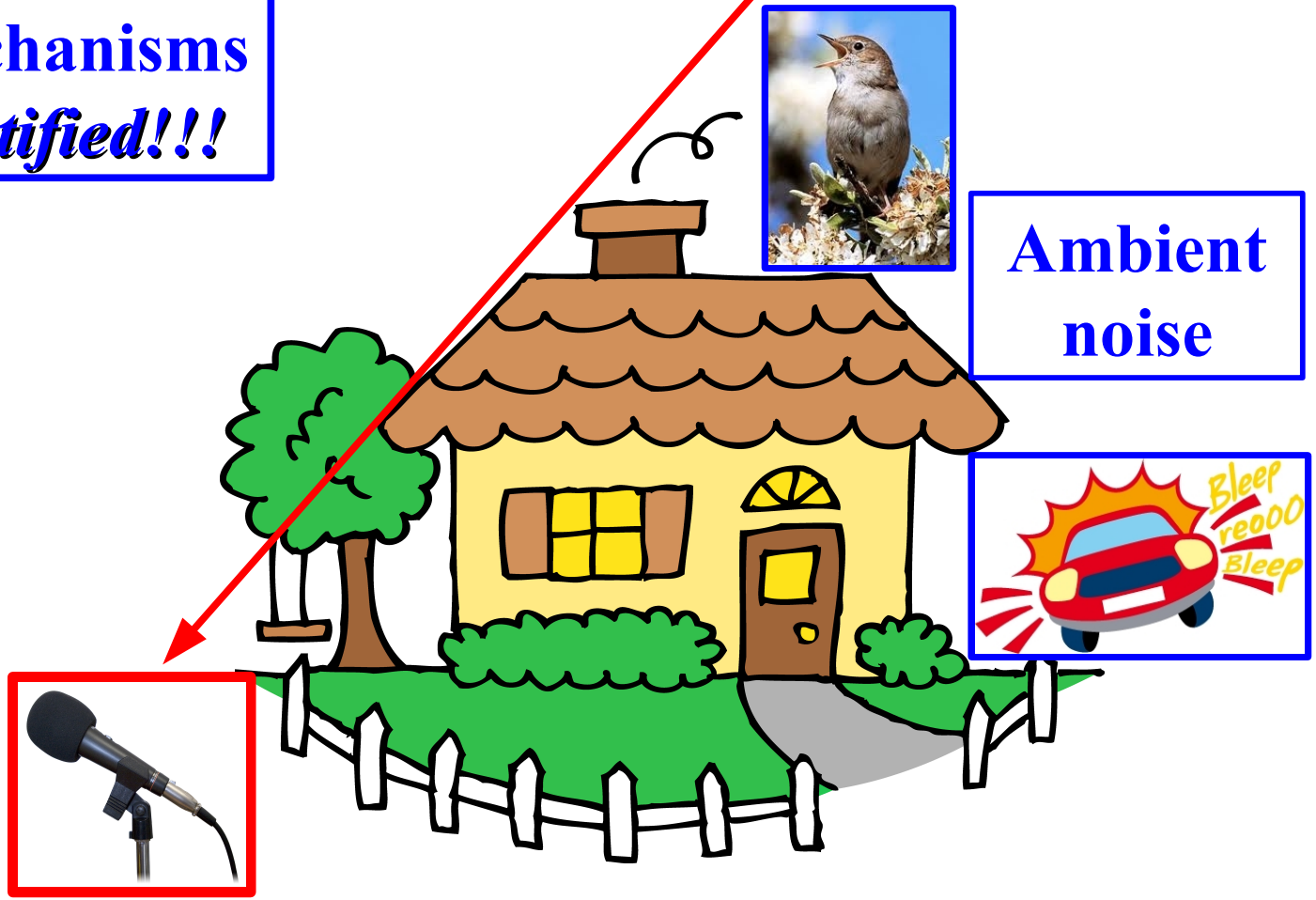
- **Physics of Sound Generation**
  - *Basic Mechanisms*
  - *Using analogies - No equations* :-)
- **Characterization of wind turbine noise sources**
  - ***Using surface pressure microphones***
  - ***Measurements performed on a 2MW wind turbine***
- **Conclusions**

Characterizing Wind Turbine Noise

Difficult to characterize in the far-field!

Individual noise generation mechanisms *cannot be identified!!!*

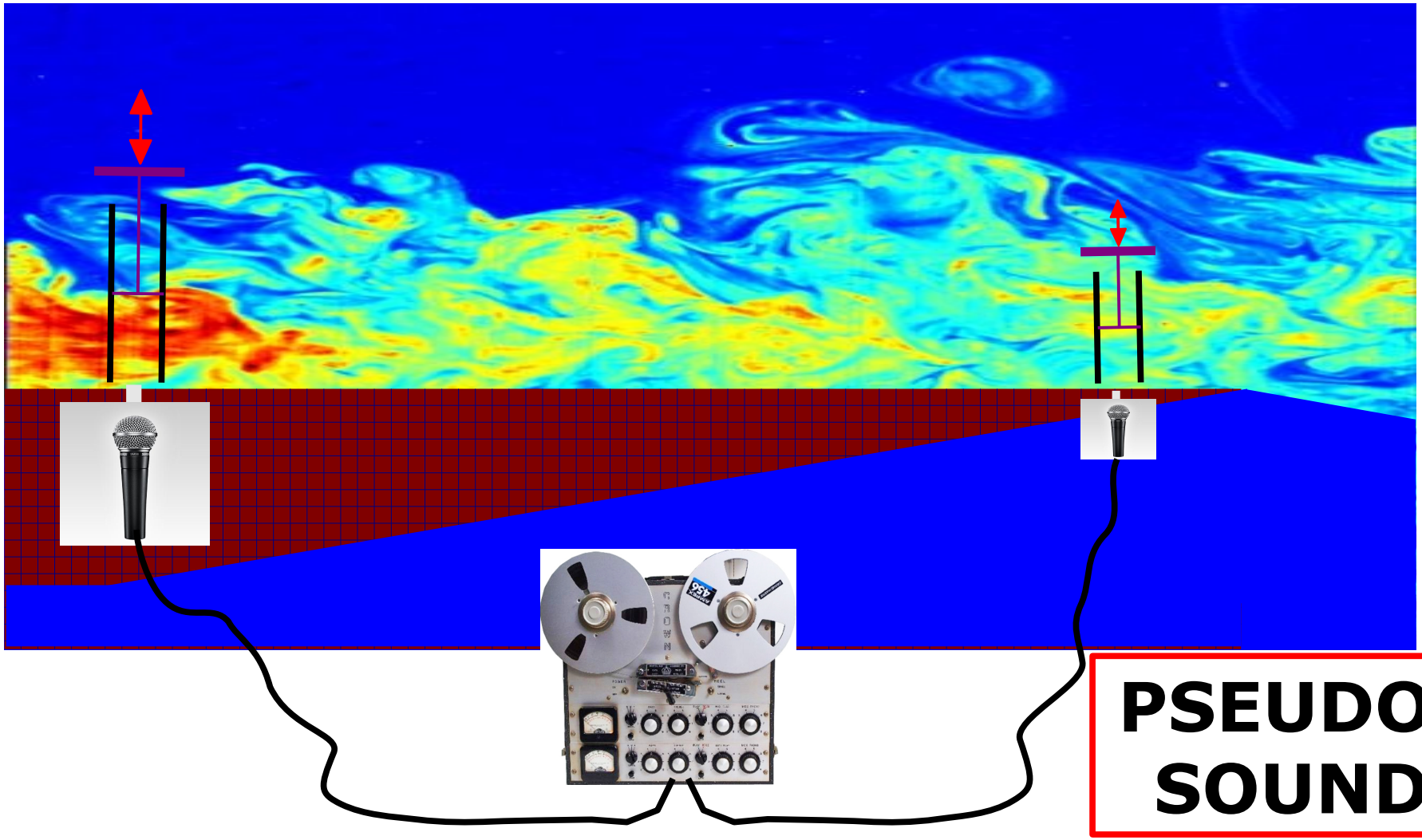




Ambient noise

Characterizing Wind Turbine Noise

Using surface pressure microphones



PSEUDO-SOUND

Characterizing Wind Turbine Noise

Surface pressure spectra = pseudo-sound
is NOT far-field noise!!!

- **Directivity / Doppler effects / Convective amplication ...**

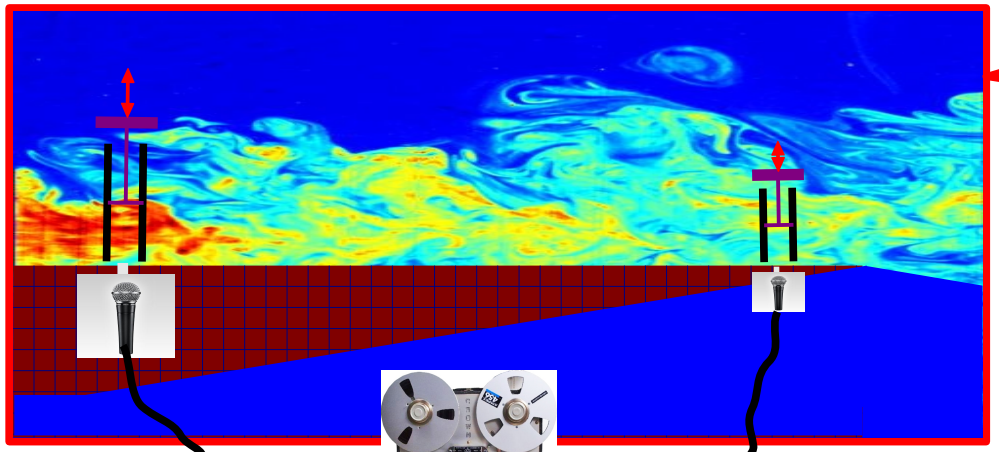
... alter pseudo-sound in near field (=1/2 rotor diameters)

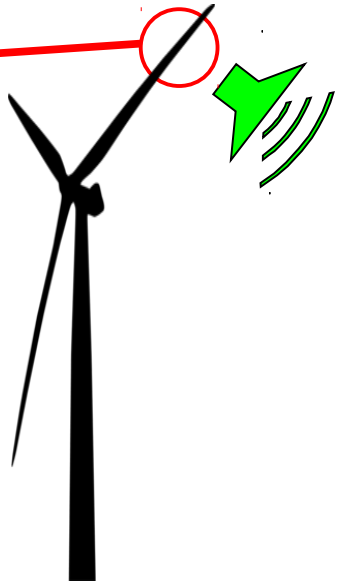
- **Atmospheric sound propagation effects including wind direction / shear-vear / stratification / etc ...**

... alter pseudo-sound in far field (=10/100+ rot. diameters)

Characterizing Wind Turbine Noise

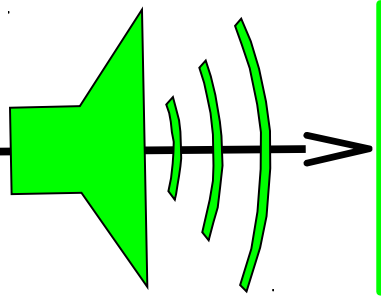
Using surface pressure microphones





Measured spectrum

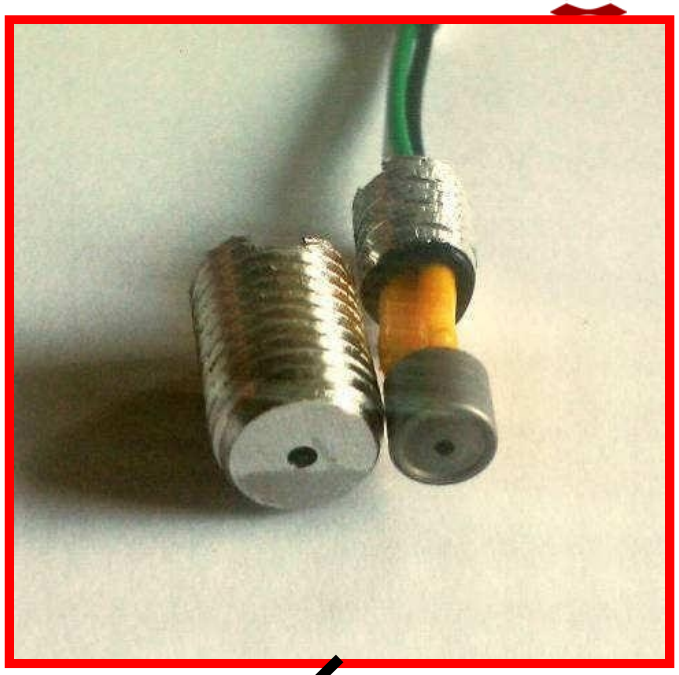
Using *mathematical formula*

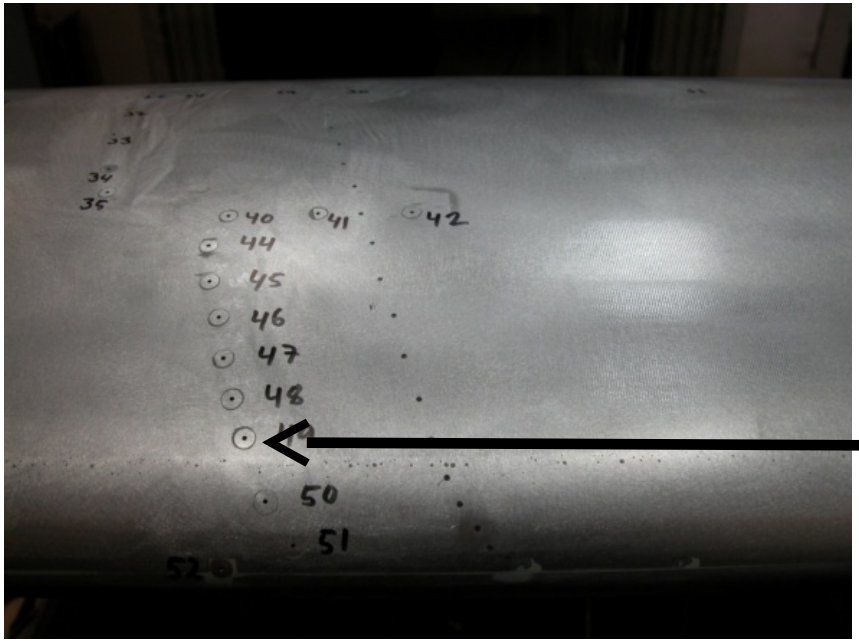


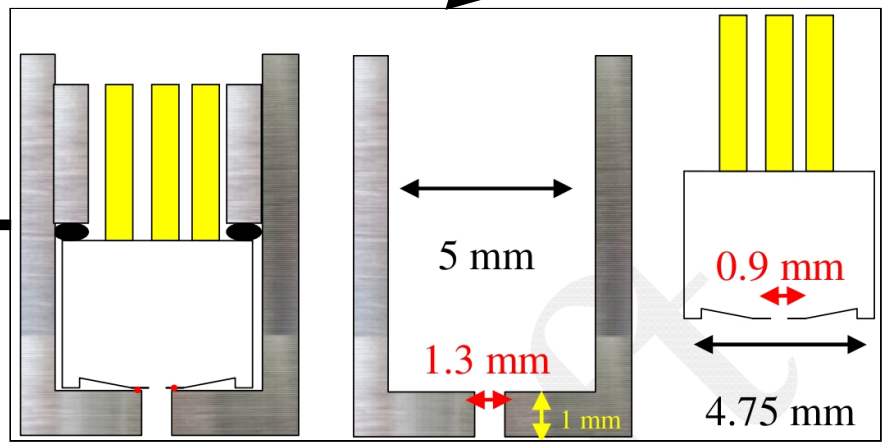
Far-field noise can be *inferred*

Characterizing Wind Turbine Noise

Surface Pressure Microphones

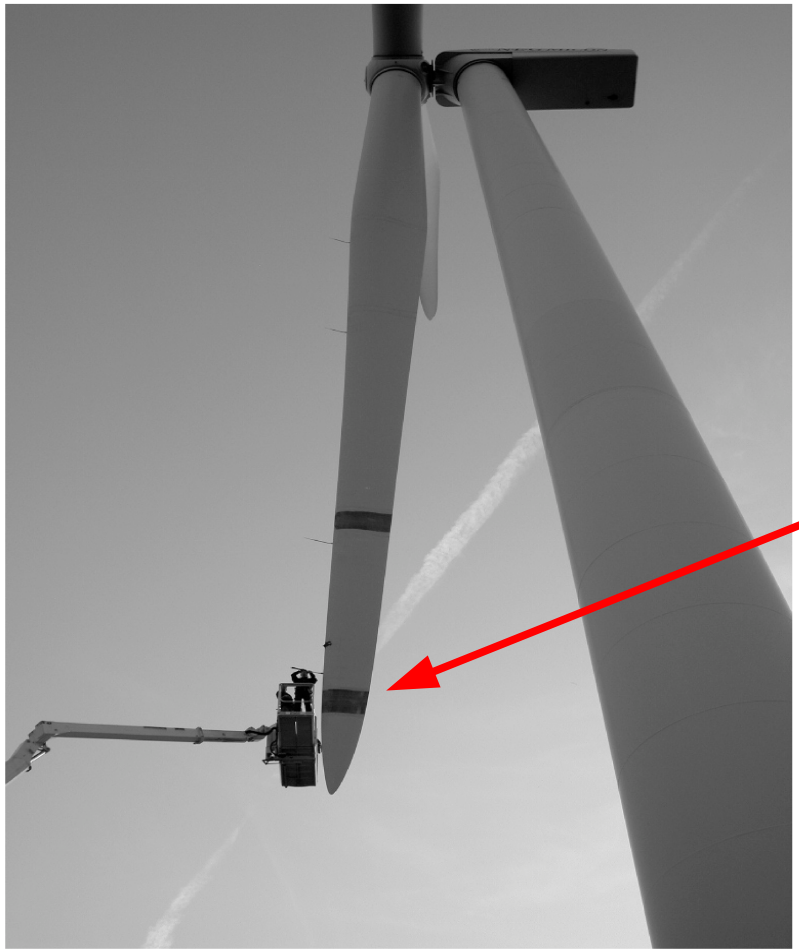


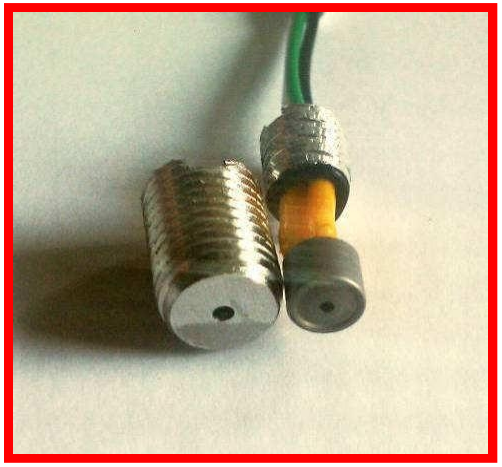




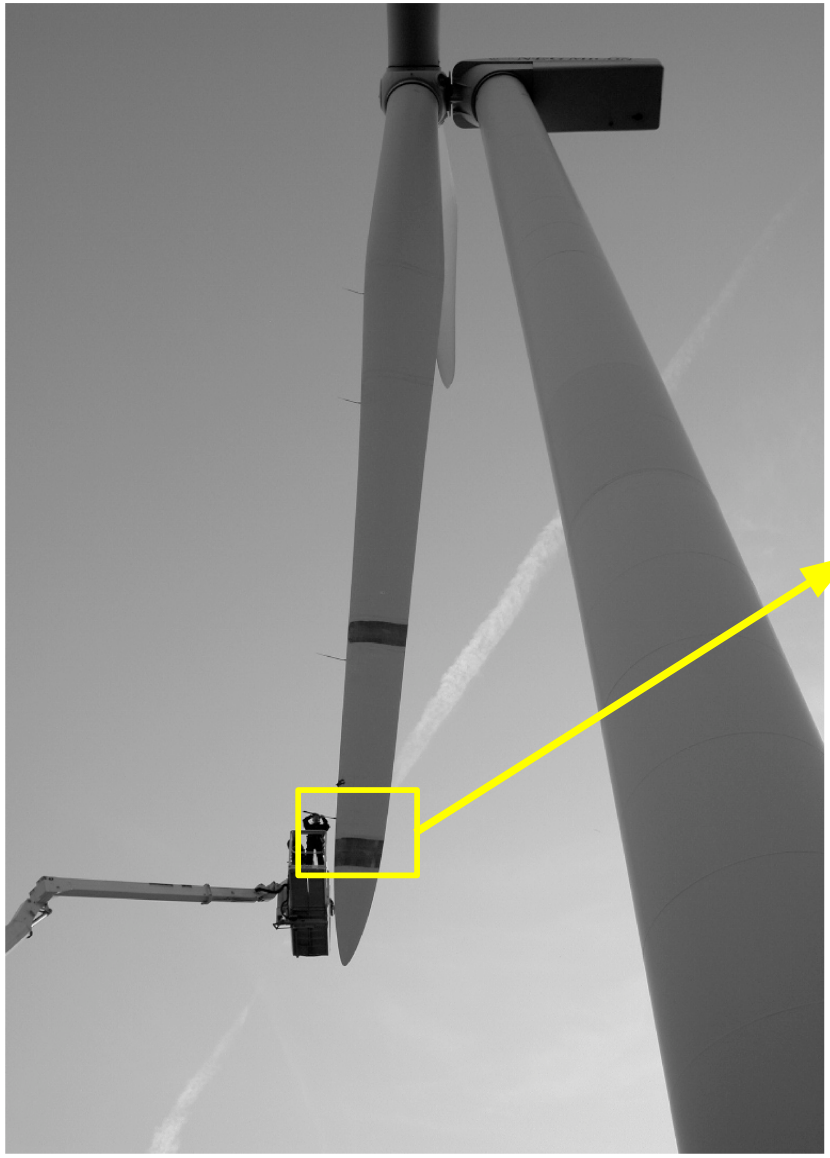
Characterizing Wind Turbine Noise

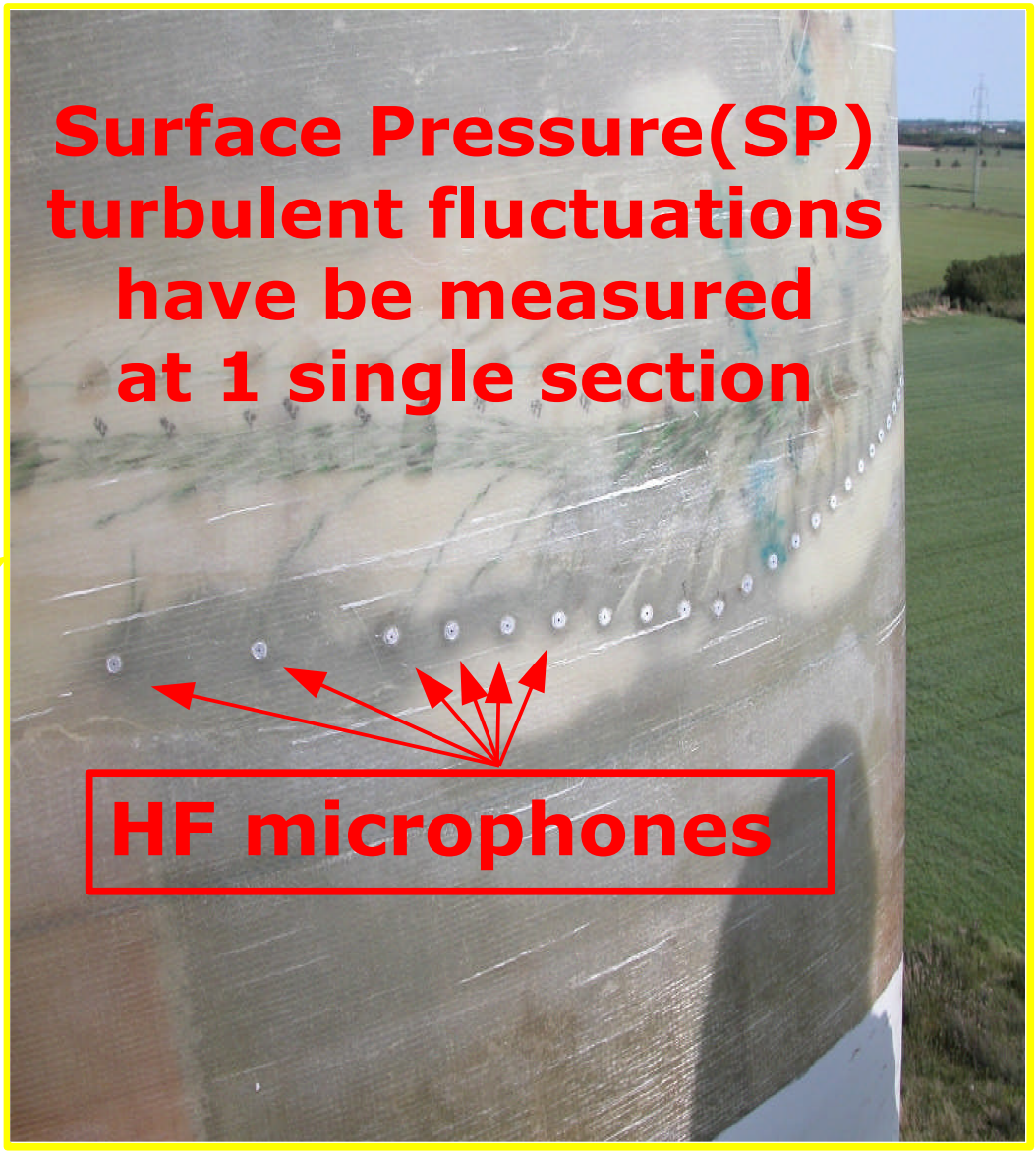
Surface pressure microphones mounted on wind turbine





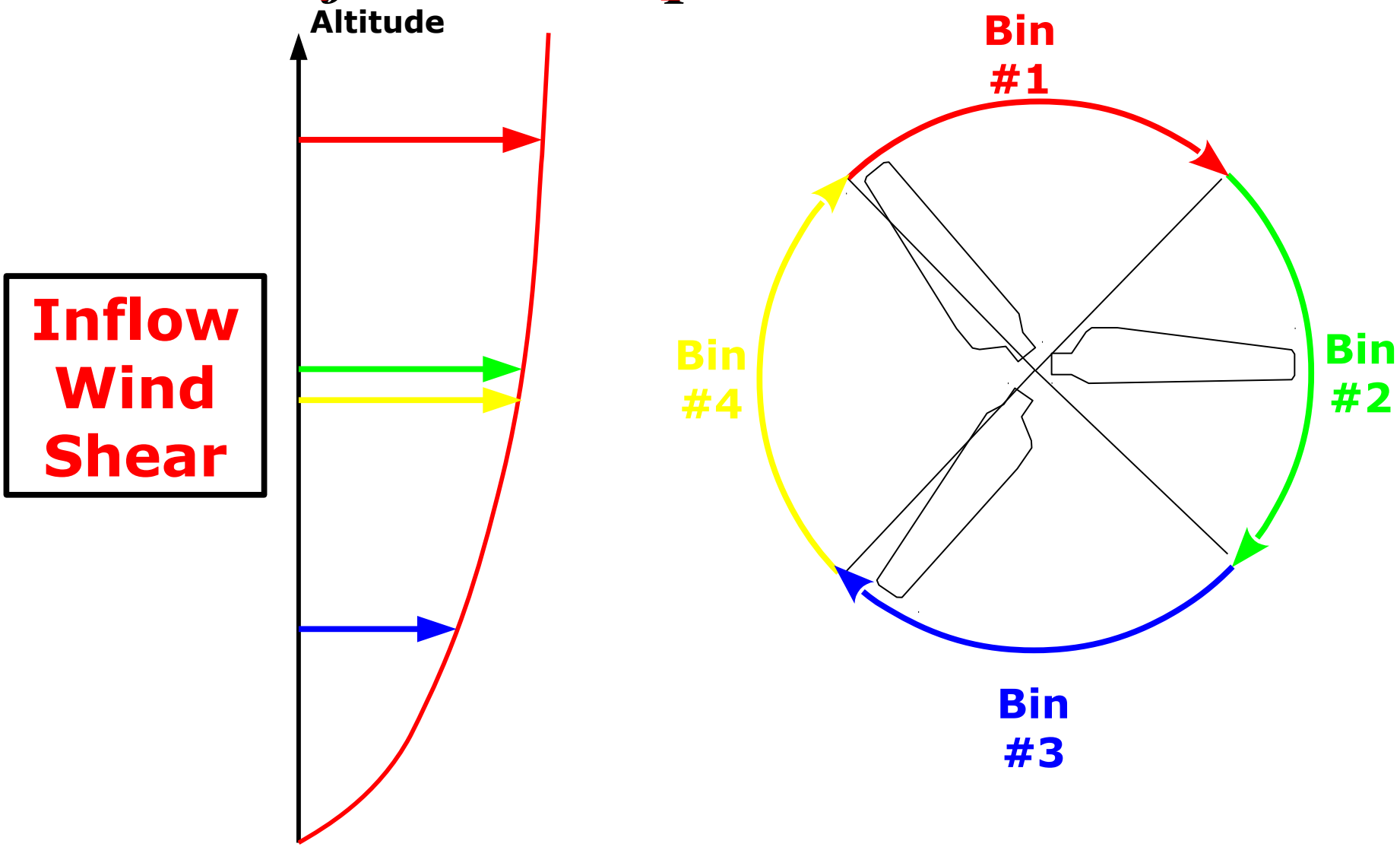
Characterizing Wind Turbine Noise





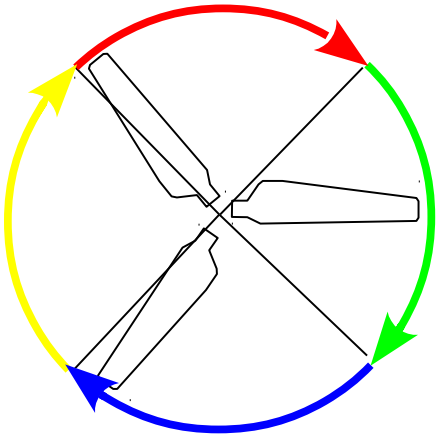
Characterizing Wind Turbine Noise: *AM*

Periodic inflow wind speed!

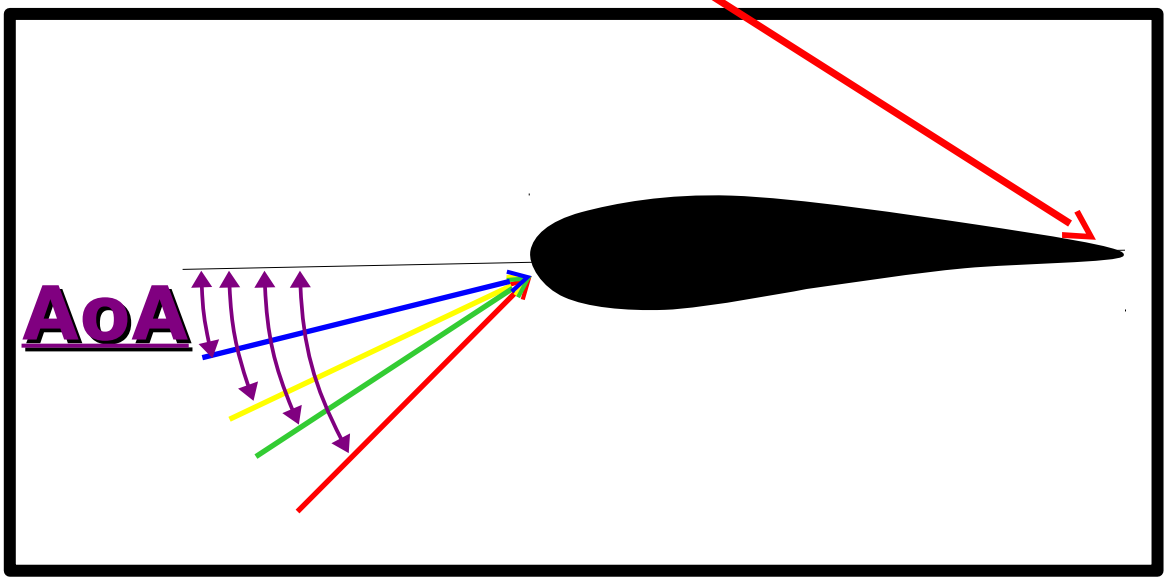


Characterizing Wind Turbine Noise: AM

Periodic angle of attack!



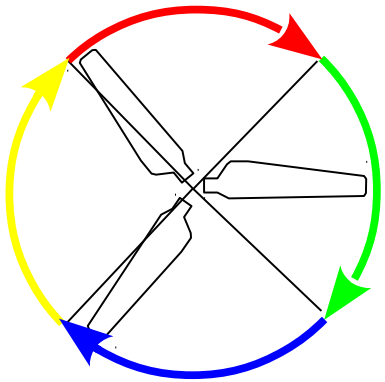
SP measured at Trailing Edge

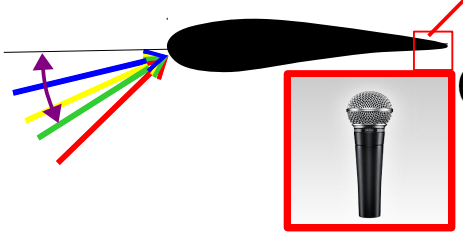


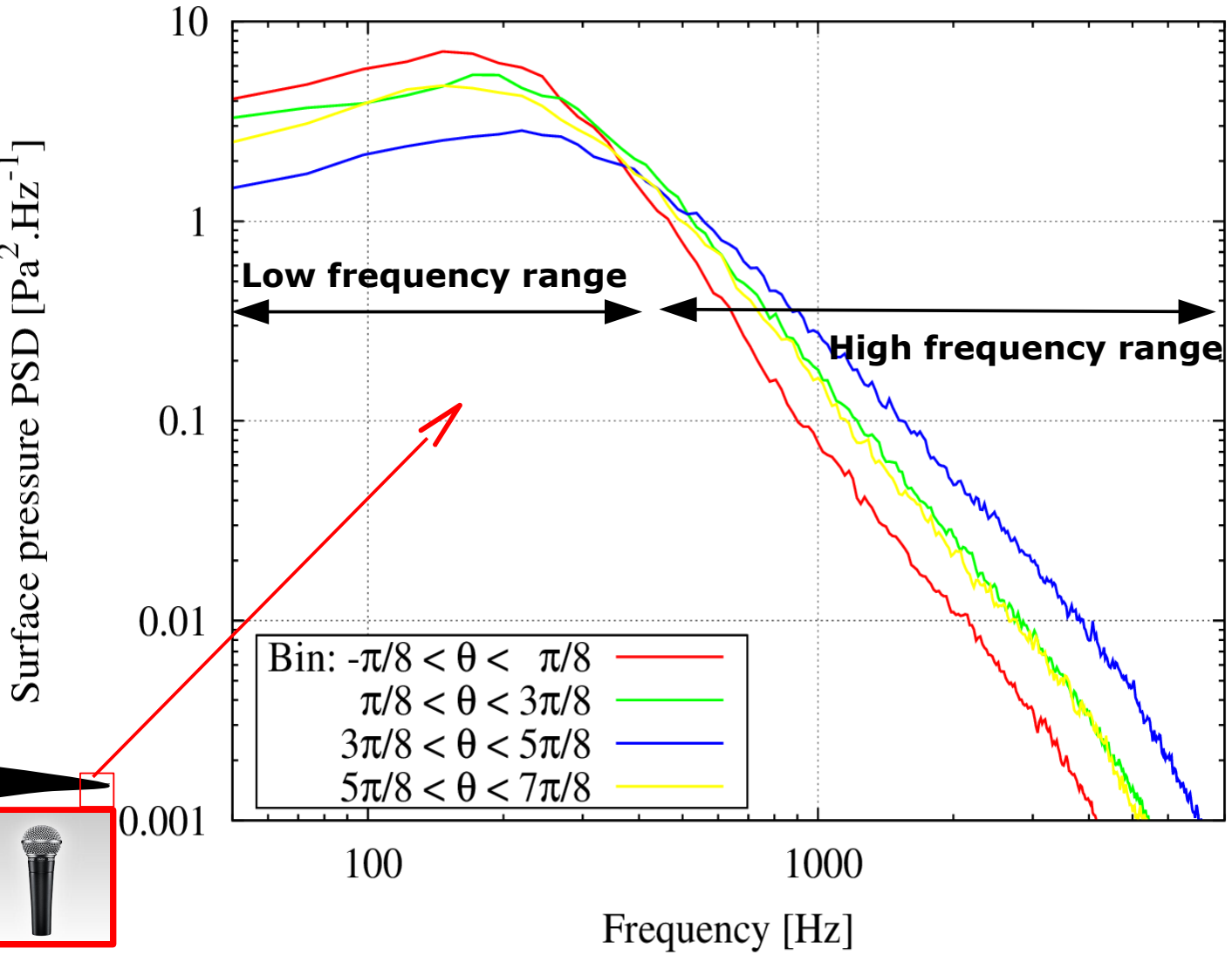
SP spectra binned according to Angle of Attack

Characterizing Wind Turbine Noise: AM

Flow periodicity results in Amplitude Modulation!



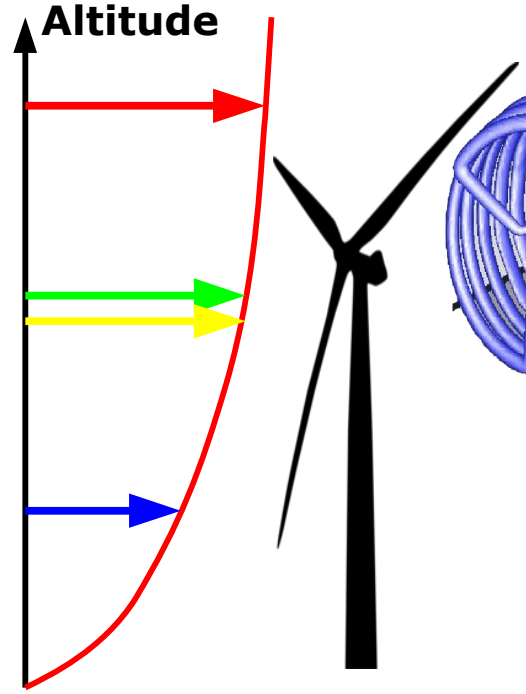




Characterizing Wind Turbine Noise: *Wake*

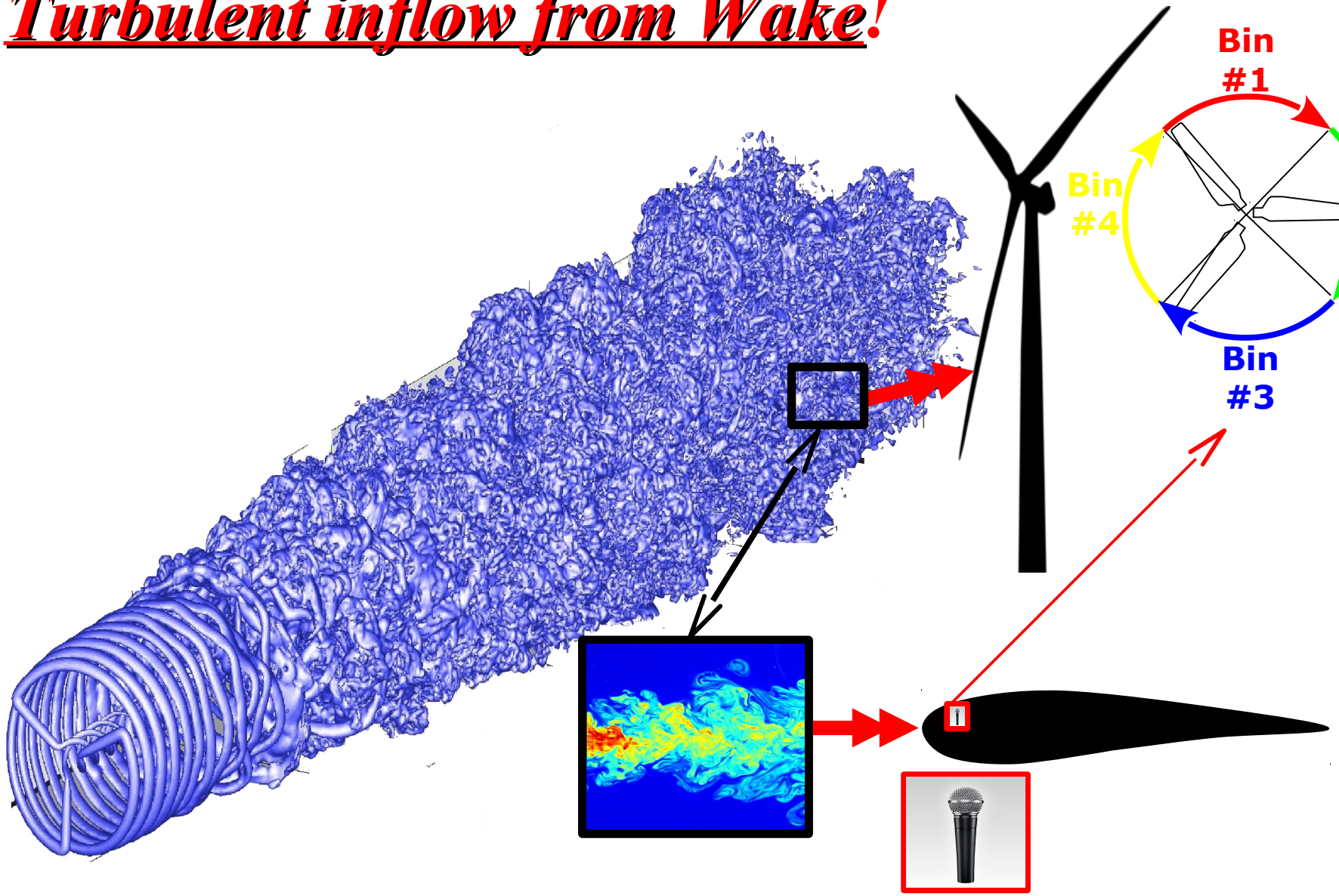
DTU

Wind turbine Wake is turbulent!



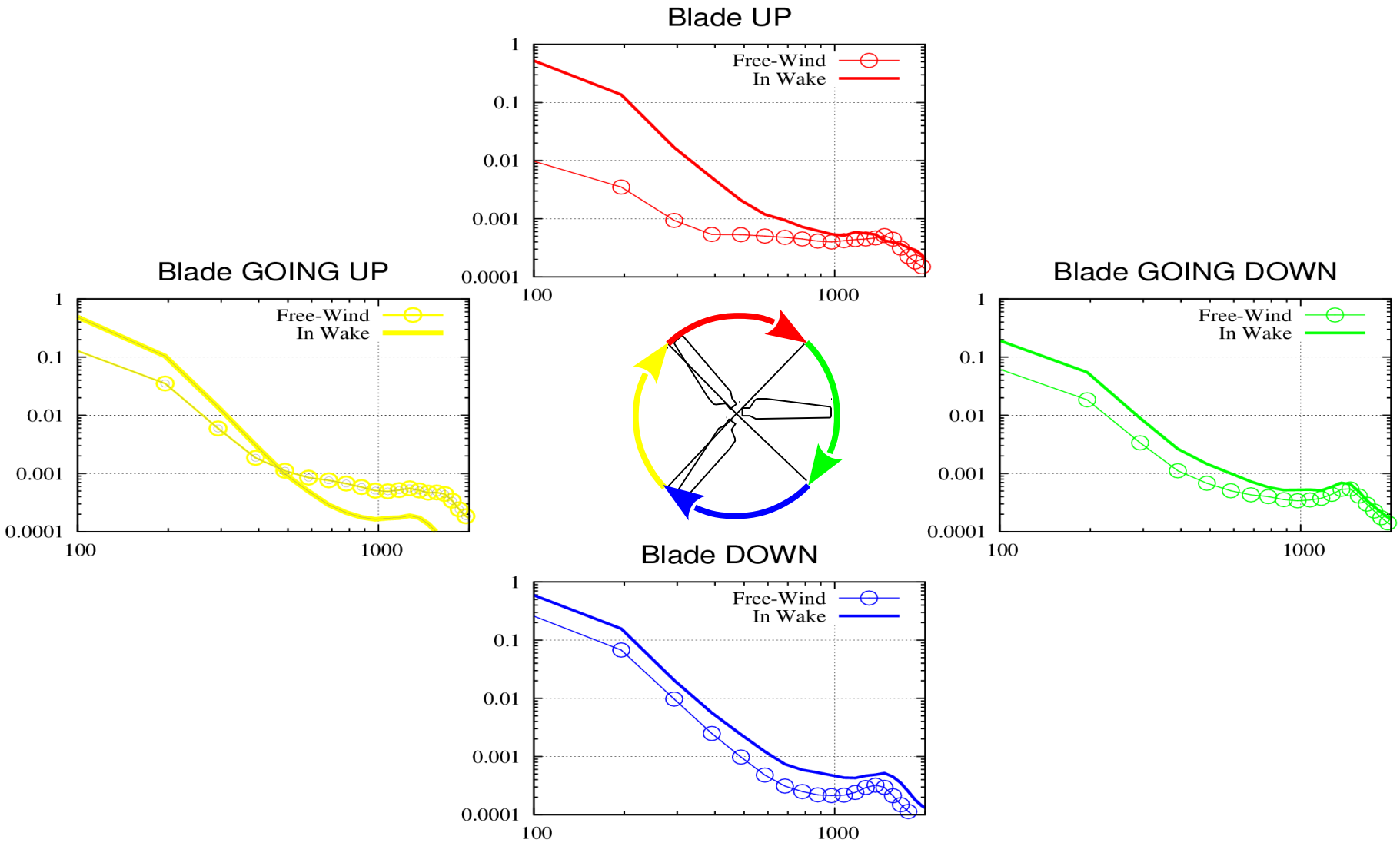
Characterizing Wind Turbine Noise: *Wake*

Turbulent inflow from Wake!



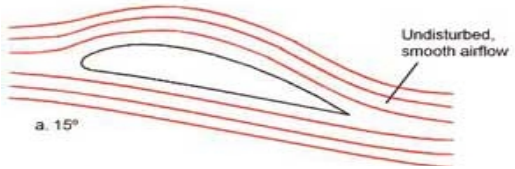
Characterizing Wind Turbine Noise: *Wake*

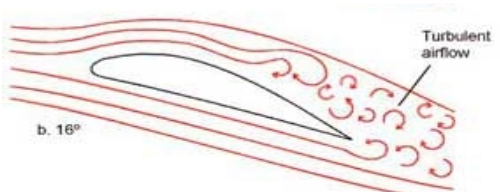
Turbulent inflow NOISE from Wake!

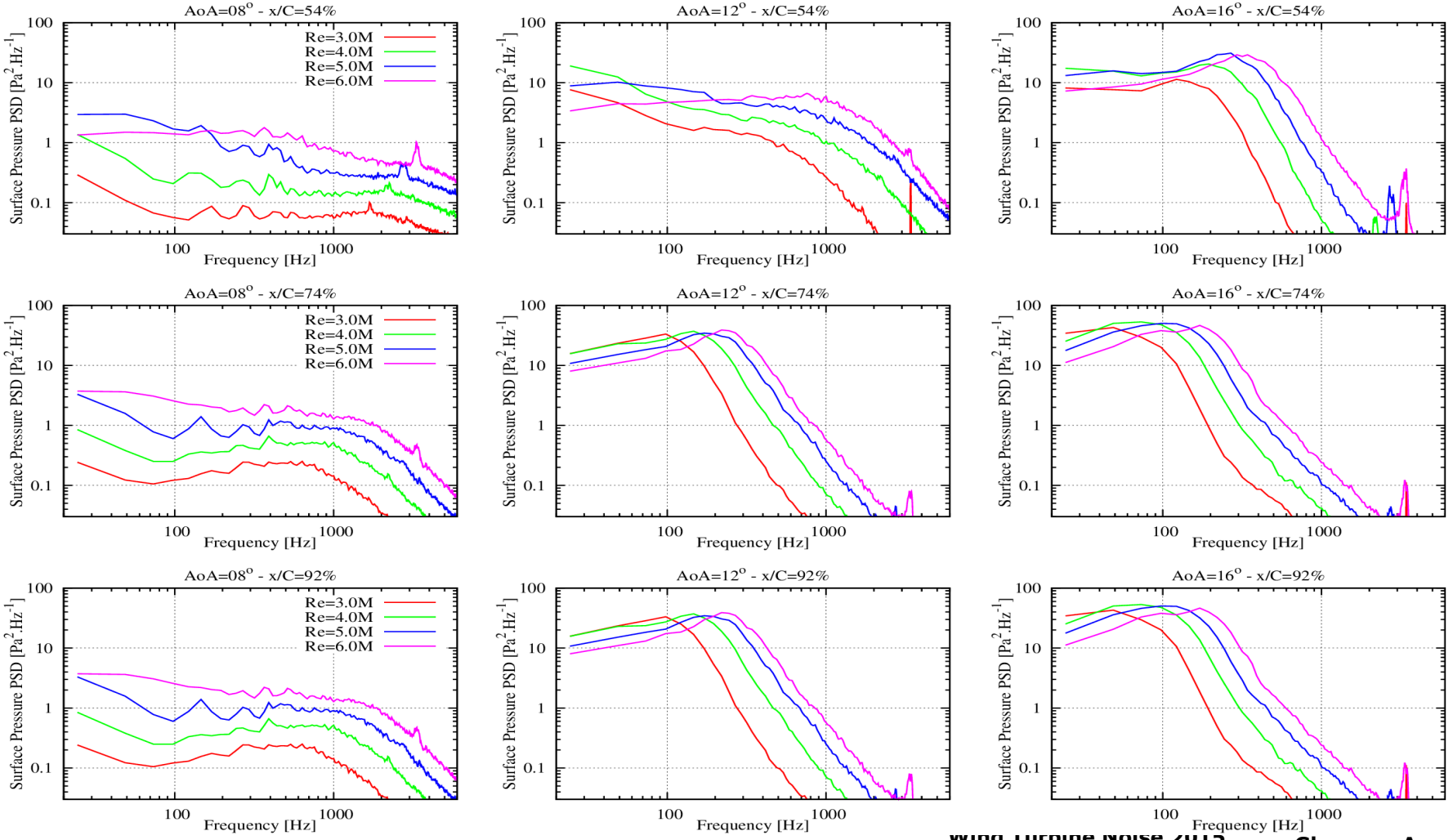


Characterizing Wind Turbine Noise:

Stall noise!







Characterizing WT Noise: Conclusions

Surface pressure measurements showed:

- **Trailing edge noise + Wind shear**

  = <u>Amplitude Modulation</u>

- **Wind turbine wake**

  = <u>Higher turbulent inflow noise</u>

- **Stall noise increases noise in range 50-200 Hz**

- **Tip noise… Could not be assessed with our experimental set-up**

Mitigation of Wind Turbine Noise

What can be done...?

- Food for thought...

Mitigation of Wind Turbine Noise

What can be done...?

- **Wind turbine farm design and siting**

  Good understanding of the *noise propagation* is the key!

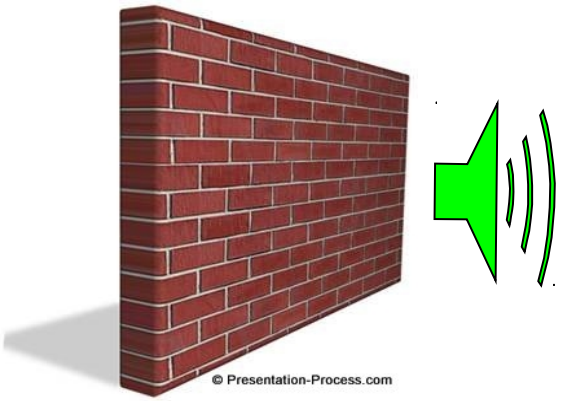
- **Deal with actual noise sources**

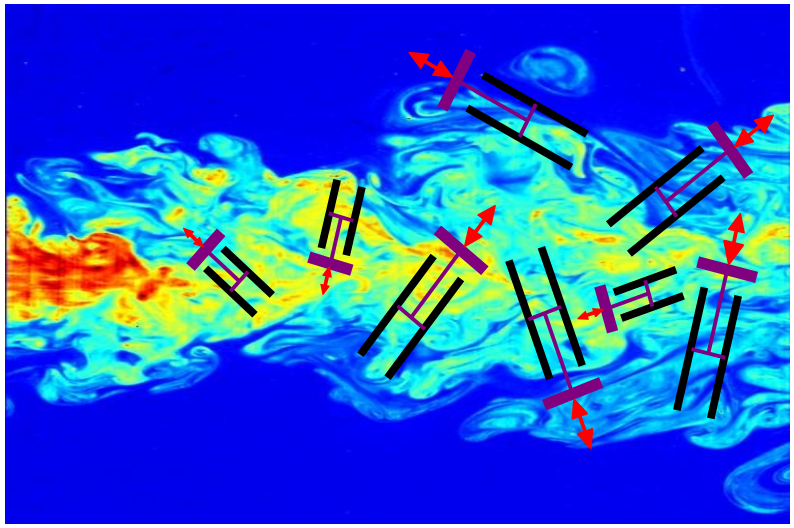
  In the perspective of the mechanisms introduced in this presentation...

- ***However, remember that the two aspects may interact (farm)... It can get really complicated!!!***

Mitigation strategy of WT noise

What can be done...?

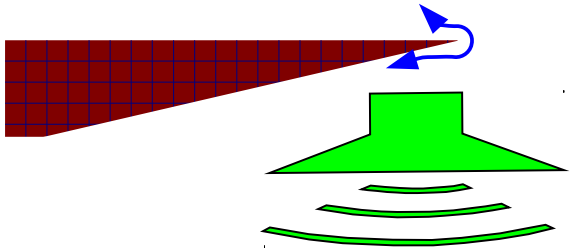




+

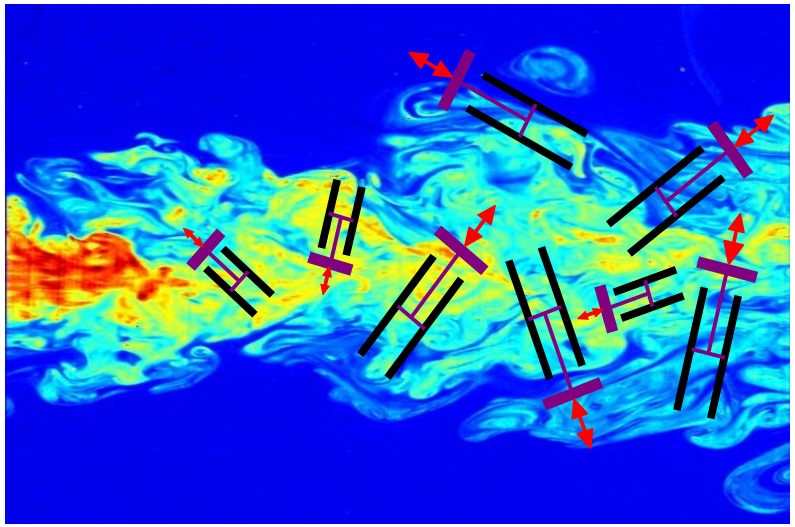
Hard surface
and
sharp edge
scattering effect

Turbulence as
noise
energy source



Mitigation strategy of WT noise

Cure #1: Reducing the turbulence intensity



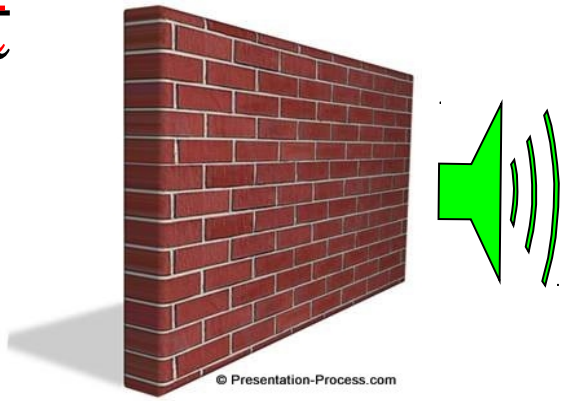
Turbulence as noise energy source

- **Alter BL development using specific airfoil design** *(e.g. by decambering – but associated with loss of energy efficiency / lift)*
- **Alter BL turbulence with active control** *(micro-jets, actuators)* **or passive ones** *(vortex generators for postponing stall)*
- **Reduce rotor speed or reduce blade pitch** *(de-rating or other WT control strategies)*

Mitigation strategy of WT noise

Altering the scattering effect

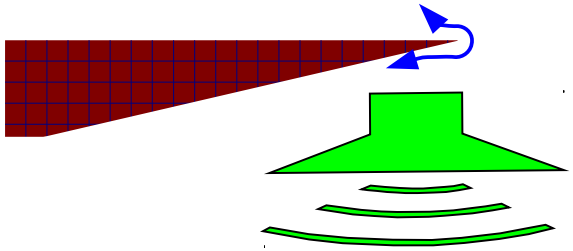
- Serrated airfoil



Hard surface
or
sharp edge
scattering effect

or

- Porous surface...



Conclusions

- **4 main noise generation mechanisms have been identified**
- **Evidence of these mechanisms on wind turbines using surface pressure measurements**
- **Some considerations on WT noise mitigation**
- ***Thank you!***